INVITED PAPER

$Hg_{1-x}Cd_xTe$ characterization measurements: current practice and future needs*

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Abstract. An extensive industrial survey of the importance and use of characterization measurements for HgCdTe materials, processes and devices has been completed. Seventy-two characterization/measurement techniques were considered and thirty-five responses were received. This information was sought for a study on materials characterization and measurement techniques of parameters and properties necessary to improve the manufacturing capabilities of HgCdTe infrared detectors. The nature of materials characterization is defined, and an overview is given of how it is related to improving IR detector manufacturing. Finally, we present a description of the characterization survey and a summary of the survey results. Major aspects of the results include: (1) ranking the 72 techniques by their importance and frequency of use, (2) listing the parameters or properties determined by each technique, (3) enumerating the most important properties that need to be measured, (4) indicating the key measurement techniques that most need to be developed, enhanced or improved, and (5) giving key overall comments.

1. Introduction

Mercury cadmium telluride, $Hg_{1-x}Cd_xTe$, where x is the Cd mole fraction of the semiconducting alloy, is the essential material for fabrication of intrinsic infrared detectors for a wide variety of military and space applications. The focus of the materials technology has evolved from small, bulk-grown wafer material to relatively large epitaxial wafers grown in special reactors with multiple capabilities. However, $Hg_{1-x}Cd_xTe$ is a complex material, and because of the large number of array elements used for imaging and the wide range of its uses, it may be ten times more complex than GaAs, and even more when compared with Si [1]. In addition, the cost and affordability of IR focal plane arrays are now of critical concern and must be addressed along with the quality and performance required [2]. It is our belief that, in order to attain high quality and top performance of IR detectors at affordable costs, enhanced understanding and use of key materials/process/device characterization methods are critical. The development of new or improved diagnostic and screening techniques will have an impact on device yields and lead to the establishment of empirical and physical models necessary for quantitative prediction of detector behaviour. Finally, we stress

that revolutionary new techniques might spring from the combination or revitalization of older ones.

Improved IR detector manufacturing may also come if US companies link their own R&D efforts involving characterization measurements more closely to the production side. As pointed out by Reich, most American technological firms draw a sharper distinction between R&D on the one side and production and marketing on the other than Japanese firms [3]. In Japan, research, product development and the design of manufacturing processes are carried out such that they are not isolated from each other. As a result, simultaneously, knowledge from one area can readily influence decisions made in other areas.

This paper attempts to describe the current importance and use of materials characterization methods now being utilized for $Hg_{1-x}Cd_xTe$ materials, processes and devices as well as to present future needs. The paper is based upon an extensive industrial survey (72 characterization/measurement techniques listed and 35 responses received) carried out over the past two years. First, in section 2, we describe the nature of materials characterization and related measurements by defining it in terms of its activities. Next, in section 3 and in three appendices, we present a description of the survey and its results. Major aspects of the survey results presented here include: (1) ranking the 72 techniques by their importance and frequency of use, (2) listing the parameters or properties

determined by each technique, (3) enumerating the most important properties that need to be measured, (4) indicating the key measurement techniques that most need to be developed, enhanced or improved, and (5) giving key overall comments.

2. Materials characterization—nature of, activities and definition

Materials characterization is an important subject. Many published papers, reports, activities and even organizational structures within industrial laboratories use these words readily. Unfortunately, materials characterization is a rather complex area, and many types of definitions and common usage, often assumed, have evolved. It is the purpose of this section to review the activities and nature of materials characterization, as well as to come up with the best overall definition that encompasses all aspects of this topic.

Over the years, many people have adopted the definition developed in 1967 by the Committee on Characterization of Materials, Materials Advisory Board, National Research Council: 'Characterization describes those features of composition and structure (including defects) of a material that are significant for a particular preparation, study of properties or use, and suffice for reproduction of the material' [4]. Hannay also seems to have adopted this approach in 1967—'In simple terms our definition of characterization means what atoms are present and where they are. This is all that is required in principle, for characterization.... Eventually, however, one hopes to understand properties in terms of composition and structure, and to eliminate the need for a description of properties, as well as the method of preparation, in characterization' [5]. Unfortunately, these definitions limit the characterization methods to those that provide information about composition, structure and defects, and exclude those methods that yield information primarily related to materials properties, such as thermal, electrical, optical, mechanical, etc. Also, some workers use on a less frequent basis the terminology 'analysis of materials' in an interrelated way. For example, Meieran *et al* (1987) in defining this subject say, 'The intent of analysis of materials is to understand material properties in order to modify them to make more usable, useful, economical objects' [6].

We give here what we feel is the broadest (and perhaps best) possible definition for materials characterization that includes its incorporation as an integral part of the manufacturing process: Activities that 'determine the *structure and composition, properties, and performance of materials, and the interrelationships among these elements.' Specific subcomponents relate to:* '(1) *structure and composition, including the development of instrumentation and its application to determine chemical and geometric descriptions of materials, from atomic to macro scales;* (2) *properties, involving the measurement of properties and their relationship to structure and composition; and*

(3) *performance, involving analysis of the behaviour of materials in simulated or actual use*' [7].

In most industrial laboratories, materials characterization measurements reflect an exceptionally diverse, multi- and interdisciplinary set of activities. The background and skills required to achieve enhanced yields of $Hg_{1-x}Cd_xTe$ IR focal plane arrays at low costs do not coincide with those of the ordinary disciplines. The scope of materials characterization in device production covers a wide range of activities—quality assurance of incoming materials, wafer screening methods, proper control and monitoring of manufacturing processes, diagnostic and failure analyses, and in playing the essential role of determining how a manufactured device differs from its intended design and function. Consequently, its importance is well established in the semiconductor industry; e.g. 'a key to the continued progress in VLSI technology is the refinement and development of new materials characterization tools.... The coupling of characterization methods to the fabrication process permits proper control of the resultant product and the tailoring of material properties to specific physical requirements, for practical applications or for fundamental studies' [8]. 'Materials characterization and device development have evolved in a synergistic partnership which has been fundamental to the semiconductor industry' [9].

The materials characterization/measurement techniques for HgCdTe materials, processes and devices listed in the survey involve three major areas of characterization: chemical and physical (or structural), electrical and optical. Figure 1 shows a simple overview of these areas, showing some representative examples, what the techniques determine and some general comments. In most cases there exists a strong interrelationship between these areas or techniques. For example, the composition of $Hg_{1-x}Cd_xTe$ greatly affects the electrical and optical properties, as well as the chemical and physical. Consequently, relevant measurements in any of the three categories of techniques shown in figure 1 can provide a determination of the composition. Obviously, intercomparisons of techniques must be carried out by correlating all the results.

3. Description of characterization survey

The survey was designed to measure the importance and use of various characterization/measurement techniques for $Hg_{1-x}Cd_xTe$ materials, processes and IR detector devices by industrial laboratories. An extensive list of 72 techniques that cover the vast majority of methods used to characterize semiconductors was assembled. Note that the authors realized that this list would not be exhaustive and so asked a general question in the survey as to what measurement techniques have been inadvertently omitted from the list. In addition, for each technique, the respondent was asked to list the key parameters or properties determined. Finally, four questions were asked at the end of the survey as shown below. The format of

the survey given out was thus as follows:

Characterization/ Measurement Technique	Technique Importance				Use of Technique					Should Use More	Key Parameters or Properties Measured By
	Don't Know	Not Imp.	Imp.	Very Imp.	Daily	Weekly	Monthly	Seldom	Never		
1. Admittance Spectroscopy											
2. Atomic Absorption Spectroscopy											
3. Atomic Emission Spectroscopy											
4. Auger Electron Spectroscopy											
⋮											
72. Surface Topography											

CHEMICAL AND PHYSICAL

Examples: TEM, SIMS, neutron diffraction/scattering, X-ray topography, photoemission, SEM, STM, AES, EBIC, ESCA, WDX, EDX, XRF, XRD, EXAFS, mass spectrometry

Comments: High spatial resolution (atomic)
Ability to identify elements and compounds
Rather complex equipment used
Interpretation of data frequently difficult
Generally lower sensitivity
Usually performed by specialists

Determines: Atomic coordination, composition, chemical bonding, elements, stoichiometry, surface topography

ELECTRICAL

Examples: Hall, resistivity, mobility, lifetime, C-V, DLTS, spreading resistance, admittance spectroscopy, quantum magnetotransport

Comments: Very prevalent
Both contacting and non-contacting methods

Determines: Carrier concentrations, lifetime, mobility, resistivity (for profiles and maps), carrier type, contact resistance

OPTICAL

Examples: Optical microscopy, ellipsometry, FTIR, PL, Raman, PR, reflectance, modulation spectroscopy, photoconductivity, LBIC, OMA, Faraday rotation, PEM, magnetoabsorption, photothermal spectroscopy

Comments: Contactless, high sensitivity
Some used routinely by nonspecialists

Determines: Optical constants; epitaxial layer and insulator thickness; optical images of surfaces; impurity and defect type and size; composition; stress/strain; damage/structural imperfections; wafer cleanliness; carrier lifetimes

Figure 1. Some simple examples of materials characterization techniques representing chemical and physical, electrical and optical measurements. Also shown are some of the properties they determine along with some general comments. The acronyms are as follows: TEM (transmission electron microscopy), SIMS (secondary ion mass spectroscopy), SEM (scanning electron microscopy), STM (scanning tunnelling microscopy), AES (Auger electron spectroscopy), EBIC (electron beam induced current), ESCA (electron spectroscopy for chemical analysis), WDX (wavelength dispersive x-ray analysis), EDX (energy dispersive x-ray analysis), XRF (x-ray fluorescence), XRD (x-ray diffraction), EXAFS (extended x-ray absorption fine structure), C–V (capacitance–voltage), DLTS (deep level transient spectroscopy), FTIR (Fourier transform infrared spectroscopy), PL (photoluminescence spectroscopy). PR (photoreflectance spectroscopy), LBIC (laser beam induced current), OMA (optical modulation absorption), PEM (photoelectromagnetic effect).

Table 1. Top twenty characterization measurements for $Hg_{1-x}Cd_xTe$ and their scores ranked in order of their importance and their use.

Imp. rank	Characterization measurement	Imp. score	Use rank	Characterization measurement	Use score
1	29. Fourier transform infrared spectroscopy	60	1	26. Etching for defects	544
2	30. Hall effect	60	2	29. Fourier transform infrared spectroscopy	537
3	11. Current–voltage	53	3	30. Hall effect	510
4	26. Etching for defects	51	4	45. Optical microscopy	483
5	45. Optical microscopy	51	5	11. Current–voltage	452
6	7. Capacitance–voltage	49	6	58. Resistivity	368
7	62. Secondary ion mass spectrometry	48	7	24. Ellipsometry	296
8	16. Double crystal x-ray rocking curve	45	8	7. Capacitance–voltage	278
9	49. Photoconductivity	40	9	16. Double crystal x-ray rocking curve	250
10	58. Resistivity	40	10	6. Breakdown voltage	241
11	60. Scanning electron microscopy	39	11	43. MOS capacitance	193
12	24. Ellipsometry	38	12	49. Photoconductivity	191
13	6. Breakdown voltage	34	13	72. Surface topography: optical interferometry, stylus, scanning tunnelling microscopy	174
14	43. MOS capacitance	32	14	60. Scanning electron microscopy	128
15	72. Surface topography: optical interferometry, stylus, scanning tunnelling microscopy	32	15	31. Laser beam induced current	88
16	4. Auger electron spectroscopy	31	16	41. Microwave impedance	80
17	15. Double crystal x-ray topography	31	17	25. Energy dispersive x-ray analysis	74
18	19. Electron beam induced current	30	18	46. Optical modulation absorption	72
19	20. Electron spectroscopy for chemical analysis	28	19	62. Secondary ion mass spectrometry	66
20	53. Photoluminescence	28	20	71. Electron diffraction	65

Questions asked:

1. What are the most important (2–4) properties or parameters to measure or determine? Why?

2. What measurement techniques most need to be developed, enhanced or improved? Why?

3. Any additional helpful, constructive comments?

4. What measurement techniques have been inadvertently omitted from this listing?
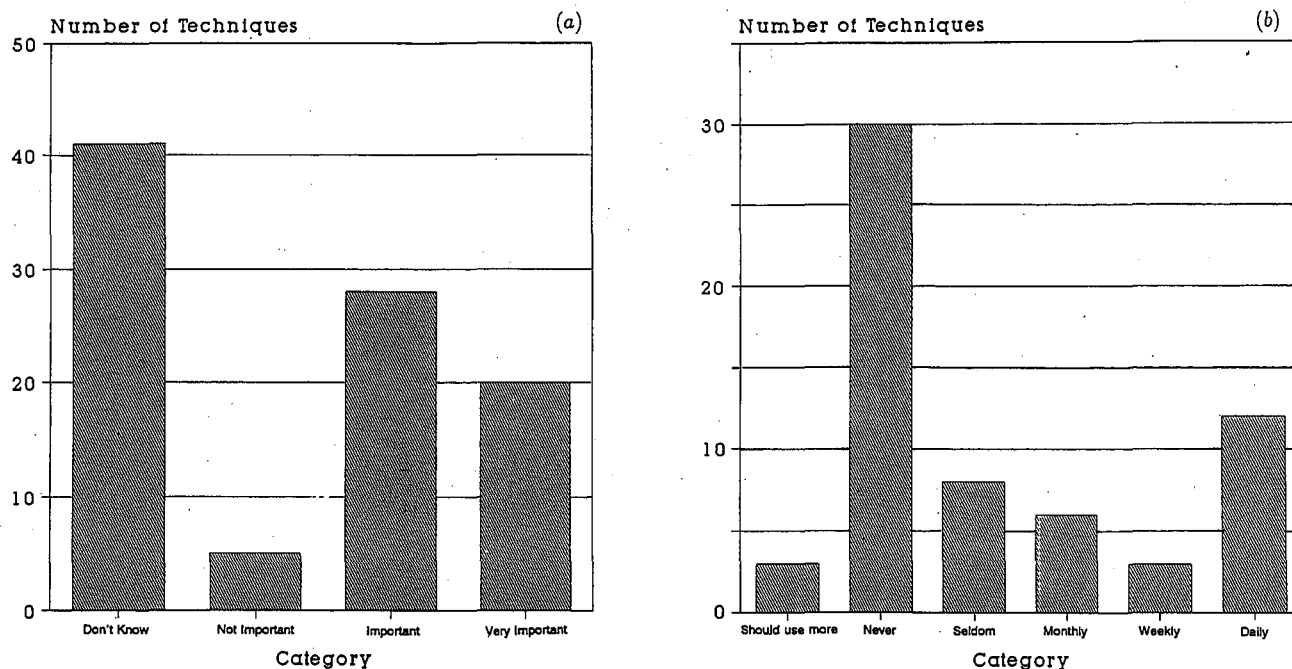
4. Survey results

The survey was distributed to numerous representatives from industry and to several key personnel at the US Army Night Vision and Electro-Optics Directorate. Two anonymous responses were also received. Among the 35 responses received, eight companies were represented. Of these company responses, the vast majority came from four major HgCdTe focal plane array producers and research laboratories. Multiple responses received from the four companies accounted for about two-thirds of the total responses received. No one company was 'over represented' in the sense that the number of respondents from each of these companies was 8, 6, 6 and 5. Consequently, the authors believe that the survey results are representative of the state-of-the-art characterization practices used in manufacturing HgCdTe infrared detectors.

The details of the survey results are presented in three appendices. Appendix 1 reports the ranking of each chracterization measurement by its importance. It was decided to weight a response that was checked 'very important' with a '2', 'important' with a '1' and 'not important' with a '0.' The top 20 techniques and their scores are listed in order of importance in table 1. In compiling the use ranking, the weight for techniques used daily was 20, weekly 4, and monthly 1. The top 20 techniques and their use score are also listed in table 1, with all the results tabulated in appendix 1.

We note the high correlation between daily or weekly usage and the importance of the technique. In some cases such as secondary ion mass spectrometry, the complexity of the technique precludes daily usage, and thus the importance rank of 7th is much greater than its use rank of 19.

Figure 2(a) shows a histogram of the number of techniques for the response for importance. If eight or more respondents said a technique was in a given category, then it was counted in that category. We note that the respondents were not familiar with a sizable portion of techniques. More strikingly, of all the rest of the techniques they were familiar with, very few (fewer than 10%) were marked 'not important'. Figure 2(b) shows a histogram of the number of techniques for the response for usage. Note that almost half are never used by more than eight of the respondents and that about 20% are used daily.

In appendix 2 are listed the respondents' comments to the key parameters or properties measured for each ·
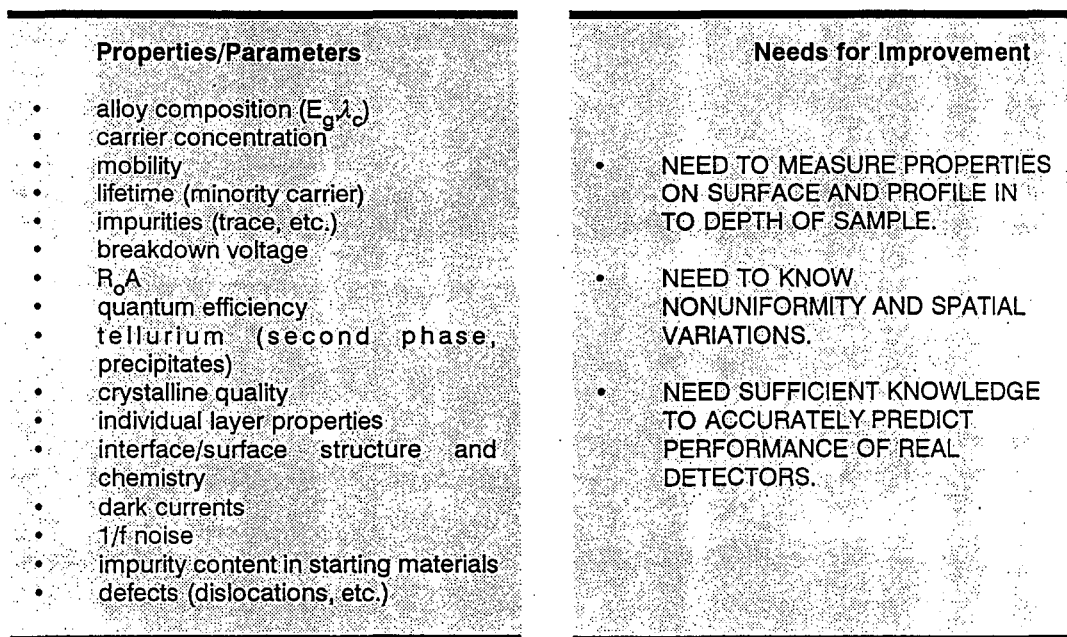
Figure 2. (a) Importance histogram for characterization techniques. (b) Usage histogram for characterization techniques. In each case a minimum of eight respondents is needed to include the technique in the category.

technique. Each respondent has been identified by a separate letter of the alphabet. Since there were 35 respondents, double letters had to be used. As can be seen from these results, the responses for each technique ranged from 0 to 25, a greater number of responses usually indicating an important or frequently used technique.

Answers to the four questions in the survey from each respondent are presented in Appendix 3. We give summaries of these answers in figures 3–6.

5. Summary and conclusions

To our knowledge, this is the first time such a characterization survey has been done for HgCdTe. We believe that results of this survey of the importance and prevalence of characterization techniques in the HgCdTe IR detector industry are important. We hope that they will stimulate and challenge existing concepts and practices and even lead to the development or application of new characterization techniques for the HgCdTe industry.

Figure 3. Summary of most important properties or parameters to measure for HgCdTe.

- anything related to device performance (defects, impurities)
- starting material analysis
- processing characterization
- device parameter measurements
- nondestructive techniques
- noncontact techniques
- techniques that cover large areas
- spatially resolved methods
- scanning methods
- mapping (of defects, concentration, composition of thickness, lifetime)
- in situ monitoring of growth processes
- characterization of multilayer structures
- material screening after growth and during processing
- defect mapping by DLTS or scanning photoluminescence
- Te cluster detection and identification
- defect detection

- detection of p-type micro islands in n-type matrix
- dark-current detection and identification
- dopant nonuniformities (sensitivity 10^{14} cm^{-3})
- surface analysis techniques - surface passivation still limits performance
- both qualitative and quantitative techniques to determine impurities or control trace amounts very early in overall process
- differential Hall effect
- Faraday rotation for nondestructive mapping of carrier concentration
- laser scanning mass spectroscopy - a good impurity survey technique?
- optical probes (PL, OMA, LBIC, etc.)
- junction location, quality, and profiling techniques

Figure 4. Summary of measurement techniques that most need to be developed, enhanced or improved.

- HgCdTe analysis is a very difficult problem. Most important question: Why do I see what I see, and what does this mean physically? Answer by carefully designing experiments combining several analytical techniques and proper controls. Focus combined efforts of materials growth, test device (or structure fab), and materials and device analysis. Multiorganizational effort is highly desirable.

- Often, materials characterization techniques and device characterization tools are developed separately. Closed loop needed between materials parameters and device-performance parameters.

- Process-control test features used in Si and GaAs industries could be transferred and/or modified for use in HgCdTe processing.

- Develop techniques for better analyses of defect states in MCT, use as more routine characterization tools.

- Establish clearinghouse of data correlated to absolute (or, if secrecy requires, relative) performance parameters.

- Establish agreed measurement standards and cross-lab correlation (as was done by NATO composition exercise in 1980).

- Standardization of surface preparation and ambient during measurements generally lacking.

- Any technique requiring >$100K investment likely to be confined to occasional research and corroboration of cheaper, less accurate techniques needed in production.

- Need to improve detection limits of various analytical techniques such as SIMS.

- Needed a column entitled, "Relative Knowledge of Technique."
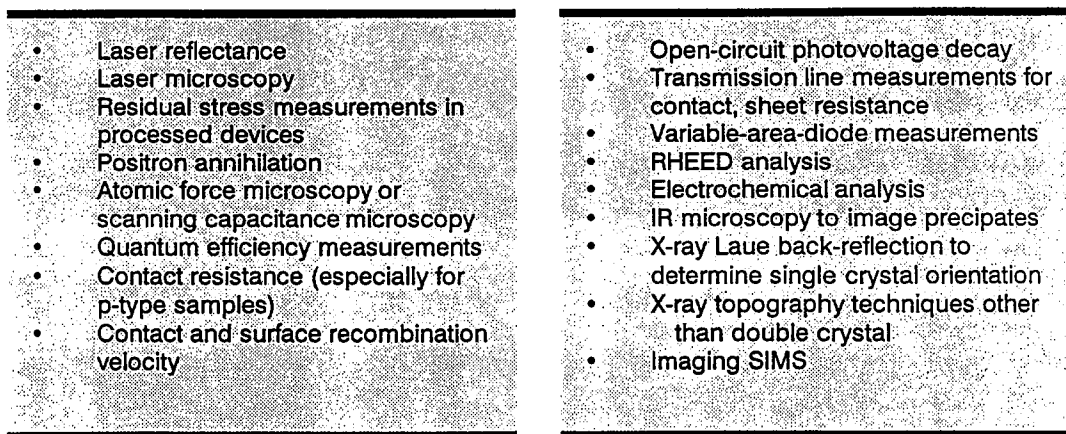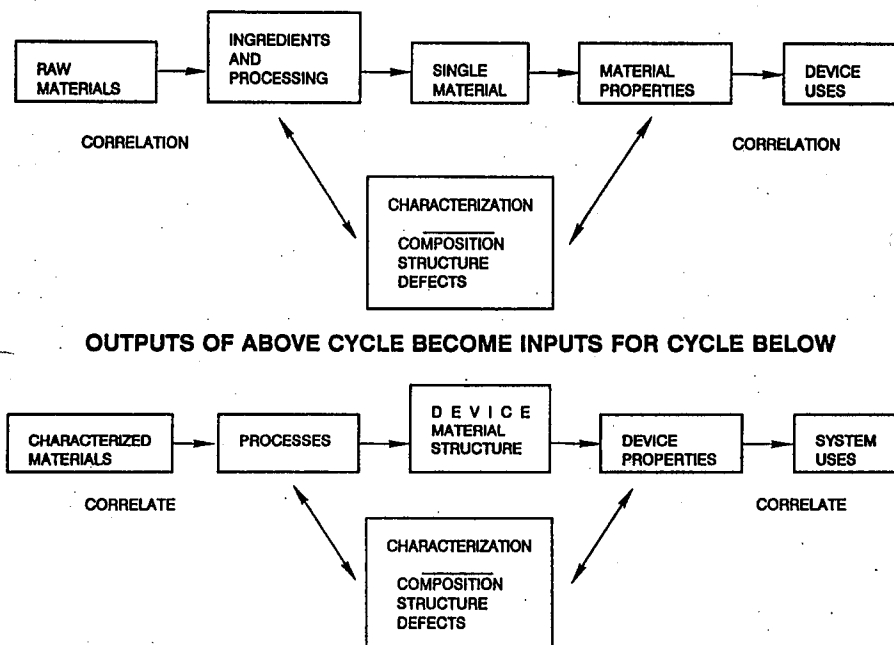
Figure 5. Summary of general comments.

- Laser reflectance
- Laser microscopy
- Residual stress measurements in processed devices
- Positron annihilation
- Atomic force microscopy or scanning capacitance microscopy
- Quantum efficiency measurements
- Contact resistance (especially for p-type samples)
- Contact and surface recombination velocity

- Open-circuit photovoltage decay
- Transmission line measurements for contact, sheet resistance
- Variable-area-diode measurements
- RHEED analysis
- Electrochemical analysis
- IR microscopy to image precipates
- X-ray Laue back-reflection to determine single crystal orientation
- X-ray topography techniques other than double crystal
- Imaging SIMS

Figure 6. Summary of measurement techniques omitted from list.

CHARACTERIZATION OF HgCdTe MATERIAL

OUTPUTS OF ABOVE CYCLE BECOME INPUTS FOR CYCLE BELOW

CHARACTERIZATION OF HgCdTe MATERIAL SYSTEM

Figure 7. Diagram of the characterization activities for a single material and a material system (see [10]). Note the strong role of characterization measurements and the need for correlation activites.

The appendices contain all the detailed results from the survey. Thus each person can individually interpret and arrive at his/her own conclusions. However, the key to success may be the *adequate use and proper combination* of many of the techniques on the list. It is worthwhile to remember that relationships exist among the structure, properties, synthesis, processing and performance of HgCdTe materials and devices as shown in figure 7 [10]. Once the material properties are characterized satisfactorily in the first part of the cycle, they become inputs for the device cycle. Important questions need to be raised and answered: how are the HgCdTe composition, structure, defects and electrical/optical properties determined by the fabrication processes, and how, in turn, does this characterization determine the useful properties of the electronic devices? Both scientific and technological issues and practices need to be thoroughly understood. Only then: (1) will HgCdTe processes and devices be capable of being controlled and continually improved, (2) can we hope to understand the physical mechanisms that affect all aspects of producing HgCdTe IR focal plane arrays, and (3) can we hope to meet the cost and reliability requirements for HgCdTe systems.

The top five measurements in order of importance are (1) Fourier transform infrared spectroscopy, (2) Hall effect, (3) current–voltage, (4) etching for defects and

(5) optical microscopy. The top five measurements in order of usage are exactly the same as for the importance ranking, but with a redistribution: (1) etching for defects, (2) Fourier transform infrared spectroscopy, (3) Hall effect, (4) optical microscopy and (5) current–voltage. The reasons for their high ranking can be ascertained from the key parameters or properties they measure, as tabulated in appendix 2. We summarize the information obtainable from them and the reasons for their high ranking.

For $Hg_{1-x}Cd_xTe$ materials, the x-value is a very important parameter to determine because, in addition to the temperature, it affects the energy band structure. The energy band structure, in turn, directly affects the cut-off wavelength, intrinsic carrier concentration, carrier mobilities, etc. The technique used more than any other is infrared transmission, most often called FTIR for Fourier transform infrared spectroscopy. The FTIR measurement has numerous advantages: it has mapping capability, it is contactless and non-destructive, and it accurately predicts cut-off wavelengths, determines layer thicknesses, and is thus capable of determining the x-value and other compositional information of epitaxial layers [11].

The Hall effect is one of the most important characterization methods because of its wide application in the determination of semiconductor resistivity, carrier concentration and mobility. Discussions of the Hall effect can be found in many solid-state and semiconductor textbooks. It has become an excellent process monitor for crystal growth with the purity, doping and homogeneity able to be correlated with growth conditions. In addition to bulk electron and hole densities and mobilities, one can determine inversion and accumulation layer properties, acceptor binding energies and compensation ratios from the low-temperature freeze-out of free holes, and energy gaps from the temperature dependence of the intrinsic carrier concentration [12].

Current–voltage measurements to determine the behaviour of diodes are very important for characterizing diode parameters. Two types of diodes may be distinguished: p–n junction diodes and metal–insulator–semiconductor (MIS) diodes. For modern-day infrared detection the p–n junction photodiode is the more important. Surface and geometrical effects become increasingly important as the detector size shrinks. Bulk defects can have impact on the operation of large arrays. Variable-area diode data analysis is an essential tool in the characterization of HgCdTe infrared detectors [13]. Measurement of the zero-bias resistance–area product (R_0A) and its perimeter/area dependence provides critical information useful in separating surface and bulk effects and evaluating the quality of the surface passivation. The junction quality can be ascertained and the diffusion,

generation–recombination and tunnelling mechanisms found. Leakage or dark currents, as well as breakdown voltages, are also important parameters that can be measured by this technique.

The physical characterization of HgCdTe crystals by etching for defects is one of the major techniques for measuring the deviation from perfection of the crystal lattice. The rate of reaction of a solution with a solid surface depends distinctly on the crystallographic orientation. The rate is also significantly affected by local stress caused by defects. Chemical etching proceeds more rapidly in regions near dislocations or any other physical defect than in perfect regions. As a result, etch pits are often formed on the surface. Etch hillocks may also form and can often be confused with pits in an optical microscope. Use of a Normarski microscope in conjunction with preferential chemical etching and optical microscopy is thus one of the easiest and least expensive techniques for the determination of crystal defects in HgCdTe. Extended crystallographic defects such as dislocations, stacking faults, precipitates, voids and subgrain boundaries can have a major impact on the performance of focal plane arrays.

Finally, we note that this paper provides a reference for the importance and use of characterization techniques in the HgCdTe community. It should be a 'handy' document for scientists or engineers who want to know what techniques are available, what they are used for, how important they are and how often they are used.

Appendix 1. Importance and usage ranking of characterization measurements

In this appendix the 72 characterization measurements are ranked by their importance (table A1) and their usage (table A2). Note that there is generally (but not always) a correlation between the importance rank and the usage rank.

Table A1. Ranking of characterization measurements by their importance.

Imp. rank	Characterization measurement	Technique importance		Imp. score I + 2VI	Use of technique			Use score 20D + 4W + M
		Imp. I	V. Imp. VI		Daily D	Weekly W	Monthly M	
1	29. Fourier transform infrared spectroscopy	6	27	60	26	4	1	537
2	30. Hall effect	4	28	60	25	2	2	510
3	11. Current–voltage	3	25	53	22	3		452
4	26. Etching for defects	9	21	51	26	4	8	544
5	45. Optical microscopy	3	24	51	24		3	483
6	7. Capacitance–voltage	11	19	49	12	9	2	278
7	62. Secondary ion mass spectrometry	10	19	48	1	9	10	66
8	16. Double crystal x-ray rocking curve	11	17	45	11	6	6	250
9	49. Photoconductivity	14	13	40	8	7	3	191
10	58. Resistivity	10	15	40	18	2		368
11	60. Scanning electron microscopy	15	12	39	4	10	8	128
12	24. Ellipsometry	12	13	38	14	3	4	296
13	6. Breakdown voltage	10	12	34	11	5	1	241
14	43. MOS capacitance	6	13	32	8	8	1	193
15	72. Surface topography: optical interferometry, stylus, scanning tunnelling microscopy	14	9	32	8	3	2	174
16	4. Auger electron spectroscopy	13	9	31	2	2	1	49
17	15. Double crystal x-ray topography	15	8	31	2		4	44
18	19. Electron beam induced current	12	9	30	1	3	3	35
19	20. Electron spectroscopy for chemical analysis	10	9	28	2	1	5	49
20	53. Photoluminescence	12	8	28		5	5	25
21	67. Transmission electron microscopy	12	8	28	1	1	8	32
22	2. Atomic absorption spectroscopy	15	6	27		1	5	9
23	25. Energy dispersive x-ray analysis	14	6	26	2	7	6	74
24	31. Laser beam induced current	16	5	26	3	6	4	88
25	14. Deep level transient spectroscopy	15	4	23			3	3
26	61. Scanning transmission electron microscopy	11	6	23	1		2	22
27	46. Optical modulation absorption	11	5	21	3	3		72
28	40. Mass spectrometry	12	4	20	1	1	7	31
29	12. Diode reverse recovery	11	4	19	2	2		48
30	13. Deep level optical spectroscopy	10	3	16		2	1	9
31	47. Photo Hall effect	10	3	16			3	3
32	64. Spreading resistance	7	4	15	1	1	3	27
33	8. Cathodoluminescence	14		14			3	3
34	71. Electron diffraction	6	4	14	3	1	1	65
35	54. Photoreflectivity	4	4	12	2		1	41
36	44. Neutron activation analysis	5	3	11	1			20
37	33. Low energy electron diffraction	4	3	10	1	1		24
38	69. X-ray photoelectron microscopy	6	2	10		1	1	5
39	70. Electron channelling	8	1	10		2	3	11
40	42. Microwave reflection	5	2	9	2	1	1	45
41	56. Raman scattering spectroscopy	7	1	9				0
42	57. Reflectometry	1	4	9	3	1		64
43	59. Rutherford backscattering spectroscopy	9		9			2	2
44	1. Admittance spectroscopy	4	2	8	2			40
45	3. Atomic emission spectroscopy	8		8			1	1
46	5. Beta-ray absorption/backscatter	4	2	8	2	0	1	41
47	21. Electroreflectance	4	2	8		1	1	5
48	41. Microwave impedance	2	3	8	4			80
49	17. Drift mobility	1	3	7	1	1	1	25
50	18. Eddy current	5	1	7	2	1	1	45
51	48. Photocapacitance	3	2	7	1			20
52	10. Current transient spectroscopy	6		6		2	1	9
53	65. Surface photovoltage	4	1	6				0
54	22. Electron energy loss spectroscopy	5		5			1	1
55	28. Faraday effect	5		5	1	1		24
56	32. Laser ionization mass analysis	4		4				0
57	37. Magneto-optics	2	1	4		1	1	5
58	68. X-ray fluorescence analysis	4		4			1	1
59	23. Electroluminescnce	3		3				0
60	34. Magnetoabsorption	2		2				0

(*Continued*)

Table A1. (*Continued*)

Imp. rank	Characterization measurement	Technique importance		Imp. score	Use of technique			Use score
		Imp. I	V. Imp. VI	I + 2VI	Daily D	Weekly W	Monthly M	20D + 4W + M
61	38. Magnetoresistance	2		2				0
62	50. Photoelectromagnetic effect	2		2			1	1
63	51. Photoemission spectroscopy	2		2				0
64	27. Extended x-ray absorption fine structure	1		1				0
65	35. Magnetoconductivity	1		1				0
66	39. Magnetophonon spectroscopy	1		1				0
67	52. Photoinduced transient spectroscopy	1		1				0
68	63. Shubnikov–de Haas effect	1		1				0
69	66. Thermal wave microscopy	1		1				0
70	9. Charged particle activation analysis			0				0
71	36. Magnetoreflectivity			0				0
72	55. Photothermal spectroscopy			0				0

Table A2. Ranking of characterization measurements by their usage.

Use rank	Characterization measurement	Technique importance		Use score	Use of technique			Use score
		Imp. I	V. Imp. VI	I + 2VI	Daily D	Weekly W	Monthly M	20D + 4W + M
1	26. Etching for defects	9	21	51	26	4	8	544
2	29. Fourier transform infrared spectroscopy	6	27	60	26	4	1	537
3	30. Hall effect	4	28	60	25	2	2	510
4	45. Optical microscopy	3	24	51	24		3	483
5	11. Current–voltage	3	25	53	22	3		452
6	58. Resistivity	10	15	40	18	2		368
7	24. Ellipsometry	12	13	38	14	3	4	296
8	7. Capacitance–voltage	11	19	49	12	9	2	278
9	16. Double crystal x-ray rocking curve	11	17	45	11	6	6	250
10	6. Breakdown voltage	10	12	34	11	5	1	241
11	43. MOS capacitance	6	13	32	8	8	1	193
12	49. Photoconductivity	14	13	40	8	7	3	191
13	72. Surface topography: optical interferometry, stylus, scanning tunnelling microscopy	14	9	32	8	3	2	174
14	60. Scanning electron microscopy	15	12	39	4	10	8	128
15	31. Laser beam induced current	16	5	26	3	6	4	88
16	41. Microwave impedance	2	3	8	4			80
17	25. Energy dispersive x-ray analysis	14	6	26	2	7	6	74
18	46. Optical modulation absorption	11	5	21	3	3		72
19	62. Secondary ion mass spectrometry	10	19	48	1	9	10	66
20	71. Electron diffraction	6	4	14	3	1	1	65
21	57. Reflectometry	1	4	9	3	1		64
22	20. Electron spectroscopy for chemical analysis	10	9	28	2	1	5	49
23	4. Auger electron spectroscopy	13	9	31	2	2	1	49
24	12. Diode reverse recovery	11	4	19	2	2		48
25	42. Microwave reflection	5	2	9	2	1	1	45
26	18. Eddy current	5	1	7	2	1	1	45
27	15. Double crystal x-ray topography	15	8	31	2		4	44
28	5. Beta-ray absorption/backscatter	4	2	8	2		1	41
29	54. Photoreflectivity	4	4	12	2		1	41
30	1. Admittance spectroscopy	4	2	8	2			40
31	19. Electron beam induced current	12	9	30	1	3	3	35
32	67. Transmission electron microscopy	12	8	28	1	1	8	32
33	40. Mass spectrometry	12	4	20	1	1	7	31
34	64. Spreading resistance	7	4	15	1	1	3	27
35	53. Photoluminescence	12	8	28		5	5	25
36	17. Drift mobility	1	3	7	1	1	1	25
37	33. Low energy electron diffraction	4	3	10	1	1		24
38	28. Faraday effect	5		5	1	1		24
39	61. Scanning transmission electron microscopy	11	6	23	1		2	22

Table A2. (*continued*)

Use rank	Characterization measurement	Technique importance		Use score I + 2VI	Use of technique			Use score 20D + 4W + M
		Imp. I	V. Imp. VI		Daily D	Weekly W	Monthly M	
40	44. Neutron activation analysis	5	3	11	1			20
41	48. Photocapacitance	3	2	7	1			20
42	70. Electron channelling	8	1	10		2	3	11
43	2. Atomic absorption spectroscopy	15	6	27		1	5	9
44	13. Deep level optical spectroscopy	10	3	16		2	1	9
45	10. Current transient spectroscopy	6		6		2	1	9
46	69. X-ray photoelectron microscopy	6	2	10		1	1	5
47	21. Electroreflectance	4	2	8		1	1	5
48	37. Magneto-optics	2	1	4		1	1	5
49	14. Deep level transient spectroscopy	15	4	23			3	3
50	47. Photo Hall effect	10	3	16			3	3
51	8. Cathodoluminescence	14		14			3	3
52	59. Rutherford backscattering spectroscopy	9		9			2	2
53	3. Atomic emission spectroscopy	8		8			1	1
54	22. Electron energy loss spectroscopy	5		5			1	1
55	50. Photoelectromagnetic effect	2		2			1	1
56	68. X-ray fluorescence analysis	4		4			1	1
57	56. Raman scattering spectroscopy	7	1	9				0
58	65. Surface photovoltage	4	1	6				0
59	32. Laser ionization mass analysis	4		4				0
60	23. Electroluminescence	3		3				0
61	34. Magnetoabsorption	2		2				0
62	38. Magnetoresistance	2		2				0
63	51. Photoemission spectroscopy	2		2				0
64	27. Extended x-ray absorption fine structure	1		1				0
65	35. Magnetoconductivity	1		1				0
66	39. Magnetophonon spectroscopy	1		1				0
67	52. Photoinduced transient spectroscopy	1		1				0
68	63. Shubnikov–de Haas effect	1		1				0
69	66. Thermal wave microscopy	1		1				0
70	9. Charged particle activation analysis			0				0
71	36. Magnetoreflectivity			0				0
72	55. Photothermal spectroscopy			0				0

Appendix 2. Key parameters or properties measured

In this appendix the key parameters or properties measured by each characterization/measurement technique are given. Each letter of the alphabet refers to a specific respondent throughout. The more important and highly used the technique, the more the responses received.

1. *Admittance spectroscopy*

   t. (On MIS) N_{ss}, flatband voltage
   w. Conductance
   dd. Deep level analysis
   ff. Interface state density
   hh. Lifetimes, activation energies, transition rates
   ii. Dark current mechanisms, activation energy

2. *Atomic absorption spectroscopy*

   d. Impurities
   f. Cu concentration in Te matrix, etc. Other impurites
   g. Used to measure impurities in raw materials and substrates. Buying instrument
   j. Fe, Cu impurity concentrations in bulk CdTe

   k. Dopant concentrations—typically In, masked by ^{115}Cd in mass spectrometry
   n. Characterization of starting materials
   o. Trace level impurities
   p. Impurities, material and source materials & gases (MOCVD)
   r. Trace element analysis, we have a contract with VHG to improve technology
   s. Impurity survey in starting materials, including organometallics using ICP
   t. Low levels of impurities, good for impurities hard to detect by SIMS
   u. Cu detection in substrates; other impurities: Si, Na, Li, etc.
   v. Zeeman corrected. Impurities in films and substrates
   w. II–VI material purity
   y. Composition
   aa. Composition, impurity concentration
   cc. *Trace impurities* in starting materials, substrates and epilayers. Use ZCGFAAS technique
   dd. Trace element analysis of raw materials and semiconductor materials
   ee. Impurity levels. Need more sensitive technique

Appendix 2 (*Continued*)

3. *Atomic emission spectroscopy*

d. Impurities
f. Survey elemental impurities
y. Composition
aa. Impurity concentration
dd. Trace element analysis of raw materials and semiconductor materials
ff. Impurity concentrations

4. *Auger electron spectroscopy*

d. Composition profiles
f. Surface analysis and passivation profiles and compositions
g. Occasionally used during array fabrication process development
j. Profiles of host elements
l. HgCdTe material composition and quality
m. Surface analysis
n. Surface impurities
o. Surface composition, interface chemistry
p. Spatial resolution high, useful in device surface analysis, passivation, metallization, interface
r. Surface element analysis and bonding
s. Surface contaminants, test of substrate cleaning
t. Composition, Te precipitates, high levels of impurities
u. Surface composition
w. Surface composition
y. Composition, especially surfaces
z. Surface chemical composition
aa. Surface composition, depth profile
cc. Surface deposits, precipitates. Use scanning AES technique
dd. Surface analysis with good spatial sensitivity—surface contaminants
ee. Surface contamination
ff. Concentrations of elements on surfaces, in films or in bulk

5. *Beta-ray absorption/backscatter*

j. Layer thickness (production line)
s. Thickness measurements when surface morphology rough
t. Nondestructive thickness determination
w. Heterojunction profiles
dd. Contactless layer thickness, metallization thickness
ee. Thickness of films on reference surface

6. *Breakdown voltage*

d. Empirical QC factor
f. Breakdown voltage in MIS
g. Measure of device/junction quality
h. Used mostly for MIS HgCdTe detectors
j. Some indication of diode quality—part of *I V* analysis
s. Indicates presence of defects that will enhance tunnelling currents; also test passivation
t. (On diodes) carrier concentration
u. Breakdown field
v. Routine characterization for MIS devices
w. Breakdown field
dd. p–n junction quality
ee. Breakdown voltage usually higher than requirement. *I–V* measurements more useful
ff. Insulator breakdown strength
hh. Material quality (tunnelling or bandgap states)
ii. Dark current mecanisms, material defects

7. *Capacitance–voltage*

d. Process control/doping
f. MIS properties, capacitance
g. Determine surface parameters—MIS. Determine junction profile—photodiodes
h. Junction doping for p–n junctions
i. Diode carrier concentration
j. Near junction concentration, interface states, V_{FB}, other MIS properties (versus temperature)
l. Material doping estimate
m. Fixed charge, interface state density, doping profile
n. Well capacity, carrier concentration
p. MIS device characteristics, passivation
s. Good technique for measuring carrier concentration in wide bandgap material
t. (On MIS, diodes) carrier concentration near the junction, flatband voltage, N_{ss}
u. Fixed charge density, carrier concentration
v. Routine characterization for MIS devices
w. Threshold voltage; carrier concentration
aa. Carrier concentration
cc. Electrical conductivity, carrier concentration
dd. Carrier concentration, quality of passivation layer (flatband, hysteresis, etc)
ee. Base layer doping extrapolate from *C–V*, capacitance itself
ff. Carrier concentration, flatband voltage, hysteresis, high/low frequency characteristics
hh. Material quality, surface passivation quality
ii. Carrier concentration

8. *Cathodoluminescence*

f. Defects in substrates
g. We're going to try some measurements
j. Some indication of CdTe or wide band MCT dislocations and impurity properties
m. Structural quality of CdTe films
o. Subsurface defect density, carrier concentration variations
r. We have used in past, may again in future
s. Indicates presence of electrically active defects but limited to MWIR or wide bandgaps
u. Electrical activity of defects such as dislocations and p/n junctions
w. CdZnTe substrate uniformity
aa. Structural defects in substrate material (CdTe, CdZnTe, etc)
cc. There is no commercial source of CL service in CdTe or CdZnTe so far as we know. *HELP*
dd. Imaging of defects of CdZnTe, have not yet used it for HgCdTe
ee. Lifetime too long to precisely locate junction (diffusion length too long)

9. *Charged particle activation analysis*

10. *Current transient spectroscopy*

d. Lifetime and junction (R_0A) product
dd. Deep level analysis
ii. Dark current mechanisms, activation energy

11. *Current–voltage*

d. R_0A
f. MIS properties, *G–V*, dark current versus bias
h. p–n junction characterization
i. Many diode parameters

Continued

Appendix 2 (*Continued*)

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j. Provides key insight both into diode performance and mechanisms (versus temperature)
l. Diode quality
m. Leakage current, dark current in photodiodes
p. Key device performance parameters, R_0A etc for photovoltaic diode
r. Diode *IV* characteristics
s. R_0A, breakdown voltage, photocurrent
t. (On diodes) origin of leakage currents
u. R_0A
w. R_0A
aa. Diode properties
dd. Junction quality
ee. R_0, $R_d(V)$, R_{series}. Model diffusion, *G–R*, and tunnelling mechanisms
ff. R_0A, leakage current
hh. Dark current mechanisms, breakdown properties
ii. Dark current mechanisms, activation energy

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12. *Diode reverse recovery*

d. Lifetime after diode processing
g. OMA and PC-rolloff to determine lifetime
h. Carrier lifetime
i. Minority carrier lifetime
j. Some idea of minority carrier lifetime near junction (versus temperature)
l. Diode lifetime
m. Minority carrier lifetime
t. Lifetime in depletion region
aa. Diode properties
dd. Recombination lifetime in diode; difficult for thin-base diodes
ee. Lifetime
ii. Lifetime, activation energy

---

13. *Deep level optical spectroscopy*

d. Check on process, deep levels, not routine (simpler than DLTS)
m. Defect density, energy level and capture cross section
r. Optical determination of impurity levels
s. Midgap states
t. Deep levels
cc. Nature of traps
dd. Deep level analysis
ee. E_T
ff. Energy of trap levels
ii. Activation energy

---

14. *Deep level transient spectroscopy*

d. Check on process, deep levels, not routine
f. Au in Si and GaAs
m. Defect density, energy level and capture cross section
n. Impurity levels
r. Looks at impurity, vacancy levels. Seems problematic for HCT
s. Midgap states, levels and concentrations
t. Deep levels
v. Desirable to correlate with device performance
w. Traps in wide bandgap II–VI materials
dd. Deep level analysis
ee. Trap levels, cross sections (expensive to use)
ff. Energy of trap levels
gg. Defect levels
ii. Activation energy

---

15. *Double crystal x-ray topography*

d. Defects—much too time-consuming
i. Defects
j. Some insight into defects and strain
k. Cd(Zn)Te(Se) substrate quality (substructure, inclusions, precipitates)
m. Structural quality over large areas
n. Crystalline perfection
p. Crystal quality bulk substrates
r. Surface topograph
s. Spatial variations in crystal quality
t. Spatial structural uniformity, defect structure
u. Crystalline perfection, precipitates, dislocation types and arrangement
v. Crystal perfection—films and substrates
w. Structural perfection of II–VI materials
y. Surface roughness
cc. Crystal perfection, defect topography
dd. High resolution imaging of defect strain field
ee. Surface crystal lattice quality

---

16. *Double crystal x-ray rocking curve*

d. FWHM of epilayers and substrates
g. Determine quality of layer, crystallinity and lattice matching with substrates
i. Crystal quality
j. Basic crystal quality of epi
l. Substrate quality; substructure, dislocations
m. Structural quality of CdTe and HgCdTe layers
n. Subject to interpretation
p. X-tal quality of epi
r. We have a Brimrose X-ray mapper. It produces both topographs and RWHM rocking curve maps
s. Crystalline quality of epilayers, tilt, strain, composition, dislocation density
t. Crystallinity
u. Microstructures/grain boundaries, etc.
v. Crystal perfection—films and substrates
w. Structural perfection of II–VI materials
y. Structural perfection
z. Crystal lattice perfection
aa. Structural properties/crystal quality
cc. Gives number related to crystal perfection. Must be in conjunction with x-ray topography or etch pitting
dd. Crystal quality, FWHM of substrates and epitaxial layers, lattice mismatch
ee. Crystal quality
ff. Linewidth, crystalline perfection
gg. Crystalline defects
hh. Epilayer quality, substrate quality

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17. *Drift mobility*

j. Basic to assessing materials electrical properties (versus temperature and field)
m. Minority carrier mobility for photoconductors
ee. Mobility

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18. *Eddy current*

f. Electrical conductivity
v. Non-destructive measurement of conductivity in films
w. Measure LPE liquidus
cc. Electrical resistivity
ee. Resistivity (no instrumentation readily available)
ii. Carrier concentration

Appendix 2 (*Continued*)

19. *Electron beam induced current*

    d. Investigation of junction location; check on BAD devices on FPAS in certain configurations

    f. Diffusion lengths, electrically active defects, mapping, junction depths

    g. Location of electrical versus metallurgical junction

    i. Junction position

    j. Junction depth, hidden junctions

    m. Diode junction location, diffusion length

    o. Subsurface defect structure, junction depth

    s. Indicates junction location and electrically active defects

    t. Junction depth in diodes

    u. p/n junction depth

    w. Type variations in HgCdTe

    dd. p–n junction location on cleaved diodes

    ee. Electrically active defect mapping, junction location, x-value, limited spatial resolution

    hh. Diode contours, junction profiles

    ii. Electrically active defect

20. *Electron spectroscopy for chemical analysis*

    f. Passivation compositions

    g. Used during process development to obtain chemical information (residue after etching, etc.)

    j. Helps assess surface contamination and processes

    l. HgCdTe material

    n. Material analysis

    o. Surface and interface chemistry

    p. Chemical surface and interface information. Compound formation during epi growth, metallization, etc, non-destructive depth profile MBE interface, electronic parameters

    r. Use along with Auger

    t. Surface chemistry

    w. Surface analysis—cleanups, passivations

    z. Surface chemical constituents

    cc. Surface chemistry, surface deposits

    dd. Surface analysis of insulators; HgCdTe composition depth profile, interface between insulator/semiconductor

    ee. Surface contamination

    ff. Chemical composition of surfaces and films

21. *Electroreflectance*

    j. Tells something about surface composition and properties, but not too clear how useful

    l. HgCdTe composition

    n. Results questionable

    s. X profile with depth

    t. Composition, E_1, E_2, Δ_0, crystallinity

    aa. Composition, bandgap

    dd. Composition, carrier concentration if calibrated. Requires ohmic contact to sample

    ee. MCT x-value

    ff. Bulk composition from E_1, material quality from linewith Γ

    ii. Composition, maybe carrier concentration

22. *Electron energy loss spectroscopy*

    o. Low Z element surface analysis, electronic states and chemical bonding

    s. Bonding of surface atoms

    dd. Used in TEM analysis to determine composition

    ee. Surface crystal diffraction patterns

    ff. Vibrational energies of phonons and adsorbates (high resolution mode)

23. *Electroluminescence*

    d. Check on junction quality

    t. (p–n junctions) radiative quantum efficiency

    ee. More useful in other material systems

24. *Ellipsometry*

    g. Thin film thicknesses and index. MCT surface state

    h. Surface preparation monitor for various parts of processes

    j. Tells surface condition, composition, film structures

    m. Film quality in detector. Passivation

    n. Film thickness and uniformity

    p. Non-destructive MBE growth control

    r. Optical constants, film thickness

    s. X profile with depth, measure dielectric layers

    t. Surface conditions, bandgap

    u. Index of refraction for insulators. (Not useful for MCT?)

    w. Surface cleanliness, film thickness

    y. ψ and Δ, n, film thickness

    z. Substrate surface contamination

    dd. Excellent measure of surface cleanliness

    ee. Surface cleanliness, film thickness

    ff. Film thickness and refractive index

    hh. Surface quality, surface contamination

25. *Energy dispersive x-ray analysis*

    f. LPE compositional profiles

    g. Occasionally used during process development. Would use more if had a good in-house one

    j. Gives gross confirmation of compositional profiles

    m. Determination of X-value in HgCdTe layers

    o. X-value, compositional uniformity

    p. Film composition average, e.g. X-value

    r. Maps of wafer X-value, impurity maps

    s. Composition analysis in thick films

    t. Compositions and their depth profile

    w. Chemical mapping on devices

    y. Composition

    z. Layer composition

    aa. Composition

    cc. Chemical nature of precipitates, Zn % CZT, chemistry of deposits

    dd. Destructive measure of composition; routine for failure analysis of processing problems

    ee. 'Bulk' composition and impurities

    ff. Bulk composition of $Hg_{1-x}Cd_xTe$

26. *Etching for defects*

    d. Defects

    f. Dislocation and Te precipitate density

    g. Qualify substrates and check growth process

    i. Defects

    j. Tells dislocation density of layer—essential to materials improvement

    k. Te precipitates, dislocations, substructure (orientation A/B)

    m. Indirect assessment of crystalline quality

    o. Etch pit density

    p. Defect measure, substrate film

    r. We don't do this, but others use a lot for material dislocation density

    s. Dislocation density

    t. Defect structure, EPD

    u. Dislocations, Te precipitates

Appendix 2 (*Continued*)

v. Dislocations—pits—inclusions in films and substrates
w. Dislocation density in HgCdTe and CdZnTe. Damage
y. Etch pit density, A–B face (111)
z. Crystal lattice perfection
aa. Defects (structural)
cc. Defect densities, dislocation nature and distribution
dd. Best technique available for determining dislocation density
ee. Correlation of etch defects with device performance
ff. Dislocation density, substructure
hh. Material quality, dislocations and other defects
ii. Dislocations, microstructure

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27. *Extended x-ray absorption fine structure*

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28. *Faraday effect*

f. Local carrier concentration
u. Is this rotation?
w. Carrier concentration in HgCdTe
ff. Carrier concentration
gg. Carrier concentration (under development)
hh. Material uniformity, $N_D - N_A$
ii. Carrier concentration

---

29. *Fourier transform infrared spectroscopy*

d. Cutoff, thickness
f. Cutoff measurements
g. Measure transmittance of substrates, films, determine X-value, device spectral response
h. Film cut-off and thickness from IR transmission spectrum. Device cut-off wavelengths and spectral response
i. Composition
j. Gives composition of film, spectral response (temperature dependence important)
k. Composition determination, IR transmission
l. Diode spectral response
m. X-value, thickness. We use double beam IR grating spectrophotometer
n. Composition, uniformity
p. Key performance parameters, absorption α
s. Composition and thickness mapping
t. Composition, gradients, thickness, far IR for transport
u. Composition (from bandgap), thickness, scattering
v. Cut-off wavelength and thickness in MCT films
w. Epilayer thickness, cut-off wavelength
y. Molecular (group) vibrational modes
aa. Cut-on λ, thickness, free-carrier absorption
cc. IR transmission, impurity effects or stoichiometric deviations
dd. Accurate, nondestructive mapping of MCT composition
ee. X-value, λ_{co}, transmission
ff. Cutoff wavelength/composition uniformity
gg. Composition
hh. Energy gap for grown material
ii. Composition, carrier type? (below bandgap absorption)

---

30. *Hall effect*

d. Transport properties
f. Material type and carrier concentration, mobility
g. Process monitor for crystal growth. Carrier density and mobility

h. Versus magnetic field is ESSENTIAL!! Versus temperature is desirable. With resistivity, gives carrier concentration and mobility. Multiple carrier effects must be taken into account in many cases
i. Carrier concentration/mobilities
j. Gives essential layer electrical properties (profile and versus B and T)
k. Electrical parameters—purity, doping, homogeneity
l. Material doping
m. μ, n, R_H, resistivity
n. Carrier concentration, mobility
p. Type determination, doping, carrier behaviour
r. Carrier type, concentration mobility. Use depends on facilities and demand
s. Carrier concentration and mobility
t. n, μ, ρ
u. N_d, mobility, type
v. Electrical properties in MCT films
w. Carrier concentration, mobility, type
aa. Carrier concentration, mobility, resistivity
cc. Bulk chemistry effects, impurities, process variations
dd. Destructive measurement of carrier concentration, mobility, resistivity
ee. μ, N_A, N_D (versus T and versus H)
ff. Carrier concentration, mobility
gg. Carrier concentration (mobility)
hh. Material type, carrier concentration, mobility; homogeneity indicator
ii. Carrier concentration

---

31. *Laser beam induced current*

d. Use on FPC diodes restricted to certain configurations. Can only evaluate drastic failure
f. Variations in electrically active defects
g. Identify active areas and location of 'breakdown'
i. Electrical uniformity
j. Helps assess material quality, junction location, optical area, etc
m. Diode junction location, diffusion length
o. Defect features
s. Junction location, electrically active defects
t. Electrically active defects, QE of diodes
u. p–n junctions in uniform MCT
w. Uniformity of HgCdTe, junction profiles
dd. Difficult to interpret results on n-type material—requires contacts to sample
ee. Defect mapping
ff. Implant uniformity, carrier inhomogeneity, diode junction position
gg. Electrically active (charged) defects, inhomogeneities
hh. Homogeneity of type of material; diode contours
ii. Electrically active defect, minority carrier diffusion length

---

32. *Laser ionization mass analysis*

f. Impurity analysis
j. Possibly better than SIMS for certain elements
s. Microanalysis of precipitates
z. Impurity concentrations
aa. Impurity
cc. Specialized impurity analysis. Might offer some lower detection limits
dd. Quantitative trace-level analysis
ee. Use SIMS instead

Appendix 2 (*Continued*)

33. *Low energy electron diffraction*

   i. *In situ* monitoring of MBE growth
   s. Surface crystalline structure
   t. Surface chemistry, lattice spacing
   y. Surface atomic order or disorder
  dd. Used as a measure of surface cleanliness and crystallinity primarily in MBE
  ee. Surface crystal quality and lattice parameters, good for MBE

34. *Magnetoabsorption*

   h. Research technique to obtain fundamental material properties
   r. Good technique for looking at impurity levels, carrier lifetime. We have no facilities for this now
   s. Fine structure
   w. Defect and impurity states in HgCdTe
  dd. NIST accurate determination of MCT bandgap versus composition and temperature

35. *Magnetoconductivity*

   h. Research technique to obtain fundamental material properties
   r. Good technique for looking at impurity levels, carrier lifetime. We have no facilities for this now
   s. Fine structure

36. *Magnetoreflectivity*

   h. Research technique to obtain fundamental material properties
   r. Good technique for looking at impurity levels, carrier lifetime. We have no facilities for this now
   s. Fine structure

37. *Magneto-optics*

   h. Research technique to obtain fundamental material properties
   r. Good technique for looking at impurity levels, carrier lifetime. We have no facilities for this now
  hh. Bandgap states investigations. Spectroscopy, transition rates
   ii. Activation energy

38. *Magnetoresistance*

   h. Research technique to obtain fundamental material properties
   r. Good technique for looking at impurity levels, carrier lifetime. We have no facilities for this now
   ii. Carrier type

39. *Magnetophonon spectroscopy*

   h. Research technique to obtain fundamental material properties
   r. Good technique for looking at impurity levels, carrier lifetime. We have no facilities for this now
   s. Coordination and short-range ordering in alloy

40. *Mass spectrometry*

   f. Impurities, dopant profiles
   g. Monitoring high vacuum processes
   j. Gives basic purity information on solid source material
   k. Low discharge mass spectrometry is routine purity control
   n. Chemical analysis
   o. Major constituent and impurity analysis

   p. Impurities of source materials
   r. Regularly used to look at film junctions, interdiffusion, impurities
   s. GCMS of starting materials can analyse for organic impurities
   t. Very important with SIMS
   w. II–VI material purity
   y. Trace elements
   z. Impurity concentrations
  aa. Trace impurity
  cc. Glow discharge MS and spark source MS are good impurity screening techniques but do not give low enough DLS. ICPMS has proved very poor in CT and CZT matrices
  dd. Trace impurity analysis
  ee. Impurity levels
  ff. Background gas composition, primary gas composition

41. *Microwave impedance*

   f. Conductivity
   u. Minority carrier lifetime
   w. Lifetime
  dd. Contactless resistivity measurement
  ee. Lifetime
  hh. Carrier lifetime

42. *Microwave reflection*

   d. Lifetime
   f. Lifetime measurements
   g. Tried some measurements with inconclusive results
   t. Minority carrier lifetime
   v. Minority carrier lifetime in MCT films
  dd. Contactless measurement of carrier lifetime
  ee. Lifetime
  ff. Minority carrier lifetime
  hh. Carrier lifetime

43. *MOS capacitance*

   f. Carrier concentration, cut-off, storage time, breakdown voltage, etc
   g. Surface passivation quality; fixed charge and surface states
   h. Monitor fixed charge at interface; measure dopant concentration
   i. Surface
   j. Basic information on flat band—important to understanding surface properties
   l. ZnS/HgCdTe passivation quality and material doping
   m. Insulator thickness
   s. Storage capacity of MIS devices or persistent currents in diodes
   t. Carrier concentration, flatband voltage, N_{ss}
   w. Carrier concentration
  dd. Surface passivation quality, carrier concentration
  ee. Surface states, surface charge: process monitor for passivation
  ff. Insulator thickness and uniformity
  hh. Material quality, surface quality
   ii. Carrier concentration—activation energy (DLTS)

44. *Neutron activaton analysis*

   f. Residual impurity analysis
   k. Special (im)purity analyses

Continued

Appendix 2 (*Continued*)

m. Impurity determination
n. For tellurium and cadmium analysis
w. Impurities in II–VI materials
cc. Good for a very few impurities in CT/CZT materials, but it has excellent DLs when applicable
dd. Trace impurity analysis
ee. Impurity determination (level)
ff. Elemental composition

45. *Optical microscopy*

d. Need automated scanning of morphology with macro–micro resolution (sampling micro)
f. Dislocation and precipitate densities, micro-structure of bulk MCT, defects, morphology
i. Morphology
j. Essential to observation of defects, layer thickness, crystal morphology and growth features
k. Surface quality
l. Fabrication and material defects
m. Surface morphology, defect determination, thickness
p. General structure of materials and devices
r. Inspection of devices and materials, IR microscope is also useful
s. Surface morphology, macro-defect density
t. Surface roughness, macro-defects
u. Surface morphology
y. Surface features
z. Surface morphology
cc. Many features of surfaces, cleaved cross sections, damage features
dd. Surface inspection/characterization
ff. Defect density

46. *Optical modulation absorption*

d. Accurate low temperature cut-off; contactless lifetime measurements; measure of junction R_0A in LWIR
g. Lifetime measurements, cut-off measurements, wafer level screening
h. Lifetime; device cut-off wavelength; film quality
j. For τ
l. Heterojunction material cut-off, response time
m. *X*-value
o. Carrier lifetime
t. Minority carrier lifetime, defect levels
w. Lifetime
dd. Contactless carrier lifetime measurement and mapping
ee. Bandgap, lifetime
ff. Carrier concentration
hh. Carrier lifetimes
ii. Lifetime

47. *Photo Hall effect*

i. Properties of minority carriers
j. For minority τ, μ
m. Influence of compensation on mobility
s. Surface states
t. N_A, N_D
u. Type, donor and acceptor concentration, mobility
hh. Lifetime measurements, transport data versus temperature, etc
ii. Activation energy, trap levels

48. *Photocapacitance*

s. Surface states
t. Defect levels

w. Detectors
ee. Used in the past with MIS structure to screen wafers for λ_{co}
ii. Quantum efficiency, responsivity

49. *Photoconductivity*

f. Lifetime
g. Photoconductive devices
h. Carrier lifetime
i. Transients for minority carrier lifetime
j. Lifetime and essential to materials/device understanding
k. Predictor of PC response—used on bulk CMT and epi EMT
m. Lifetime
p. Lifetime measurements
r. Pulse decay lifetime measurements for material lifetime and surface recombination
s. Minority carrier lifetime
t. Minority carrier lifetime, PC decay on diodes gives R_0A
w. Detectors, lifetime
cc. Might correlate to purity and stoichiometry
dd. Carrier lifetime measurement (transient)
ee. Lifetime PC device
ff. PC lifetime
gg. Lifetime
hh. Material quality, spectral response, lifetimes
ii. Lifetime, surface recombination velocity

50. *Photoelectromagnetic effect*

ee. Device parameters
hh. Minority carrier versus majority carrier effects

51. *Photoemission spectroscopy*

s. Bonding of dopants and impurities
w. Surface analysis
ff. UPS—measures valence electron energies; XPS—see ESCA

52. *Photoinduced transient spectroscopy*

cc. Traps and defects, impurities, and the way they are tied up in materials
dd. Needs development work

53. *Photoluminescence*

d. Compositions/lifetimes (77 K)—this technique is definitely underutilized in epilayer. Also substrate evaluation of low temperature 4 K
g. Compositional measurement
h. Carrier lifetime; surface quality
j. Provides some useful information on CdTe substrate quality
m. Measure crystalline quality of CdTe epi
n. Characterization of substrates
p. Non-destructive electronic characteristics measurements
s. Important for wide bandgap (defects, impurities, etc)
t. Non-radiative centres (distribution), shallow levels, Te precipitates
u. Very useful for substrates (Cd, Zn)Te. Acceptor levels/donor levels/E_g/[Zn] concentration
w. Wide-gap II–VI materials purity and defects
z. Impurities
aa. Impurities, composition, crystal quality
cc. Optically active impurity and defect states; effect of various annealing treatments

Continued

Appendix 2 (*Continued*) ·

    dd. Primarily used to determine composition of
           CdZnTe (77 K meas. temp.)
    ff. CdTe perfection
    hh. Material quality, defect bands, particularly
           epilayers

54. *Photoreflectivity*

    d. More accurate surface X-values. Also surface state
        evaluation
    p. Film composition, X-value, non-destructive MBE
        growth control
    r. HCT X-value at the surface; formerly used frequently,
        equipment currently down
    s. Alloy composition
    t. Composition, E_1, E_2, Δ_0, crystallinity
    aa. Surface composition
    dd. Contactless compared with electroreflectance
    ff. Composition (X-value)
    ii. Composition—carrier concentration?

55. *Photothermal spectroscopy*

56. *Raman scattering spectroscopy*

    j. Tried to get surface information (not sensitive).
        Bulk information not clear as to importance
    p. Crystal lattice quality and imperfections
    t. Te precipitates, composition
    w. Clustering in II–VI materials
    y. Molecular species, group vibrations
    dd. Surface ordering, not much work done for HCT
    ff. Vibrational modes of compounds
    ii. Phonon energies, defects? (anti-site)

57. *Reflectometry*

    g. UV–vis reflectance used to determine X-value
    h. Reflectance spectrum near the E_1 and $E_1 + \Delta_1$
        transitions. Gives x at the surface
    s. Alloy composition
    dd. UV reflectance (E_1 transition) used to map surface
        composition of MCT (300 K meas.)
    ee. Surface X-value

58. *Resistivity*

    d. Part of Hall process
    f. Hall measurements, determination of p-type
       material
    g. Part of Hall measurement
    i. With Hall for CC and μ
    j. With Hall, gives mobility—essential to materials,
        understanding and device modelling
    k. Electrical parameters (with Hall)—purity,
        doping, etc
    m. Carrier concentration, contact resistance
    s. Deduce mobility in conjunction with Hall
        measurements, contact resistance
    t. Product of carrier concentration and mobility
    w. HgCdTe for photoconductors
    cc. Impurities, defects, stoichiometry, annealing effects
        and effectiveness
    dd. Integral part of Hall effect measurements: not
        separately measured
    ee. Done in conjunction with Hall effect
    ff. Resistivity of metal film or semiconductor
    gg. Mobility
    hh. Material type, carrier concentration mobility;
        homogeneity indicator

59. *Rutherford backscattering spectrometry*

    f. Passivation characterization and implant profiling
    j. Provides information on near-surface composition
        and damage
    m. Chemical analysis, crystal perfection
    s. Composition depth profiles, crystallinity and strain
    y. Atom %
    dd. Crystallinity of epitaxial layers, ion implantation
        damage, etc
    ee. Passivation layer purity (hard to use for MCT)
    ff. Film composition, density

60. *Scanning electron microscopy*

    d. Morphology
    g. Important for process development
    j. Key to detailed morphology examination
    l. Fabrication/material analysis, especially defects
    m. Surface imaging, defects
    n. Defects
    o. Morphology, crystalline quality, chemical
        composition, etc
    p. Surface features
    r. Used for materials and device inspection
    s. Morphology, layer thickness
    t. Morphology
    u. Surface morphology, composition by WDX, EDAX
    v. Surface defects and other features
    w. Device examination
    y. Microstructure
    z. Surface morphology, crystallinity, thickness
    cc. Surface damage, surface features, surface deposits
    dd. Routine characterization of materials and devices
    ee. Structural micro-features
    ff. Step coverage, surface morphology

61. *Scanning transmission electron microscopy*

    f. TEM of defects
    g. Locating inclusion, dislocations, etc
    m. Dislocation density
    n. Defects
    p. Interface structure
    t. Defect structure
    y. Defect structure
    dd. Presently use TEM only
    ee. Defects. Difficult to use
    ff. Presence of dislocations, twinning
    hh. Defect quality of material, interfaces

62. *Secondary ion mass spectrometry*

    d. Impurities
    f. Chemical analysis of dopant profiles and
        impurities
    g. Determine impurity locations, dopant versus
        X-value profiles
    h. LPE film composition and impurity profiles
    i. Impurities
    j. Key to materials purity and composition and
        interface control
    l. HgCdTe heterostructure material composition,
        impurities
    m. Impurity determination
    n. Analysis of impurity clusters
    p. Impurity doping profiles
    r. Regularly used to look at film junctions,
        interdiffusion, impurities
    s. Impurity analysis and depth profiles
    t. Impurity concentration (profiles), composition

Appendix 2 (*Continued*)

u. Measure concentration of various impurities in MCT and (Cd, Zn)Te
w. Impurities in II—VI materials
y. Trace elemental analysis
z. Impurity concentration
cc. Depth profiling of trace impurity and dopant concentrations, interface or surface pile-ups, segregation effects
dd. Trace level analysis, doping profiles
ee. Impurity levels
ff. Elemental composition, implant depth
gg. Profiling of impurities, and composition

63. *Shubnikov–de Haas effect*

s. Interface states and band bending

64. *Spreading resistance*

g. Important for FPA (staring)
h. Gives contact resistance
j. Spatial information
l. Use trans. line method → contact resistance
s. Sheet resistance
t. Transport, $n\mu$ product
w. Conductivity uniformity
dd. 77 K spreading resistance technique to profile p–n junctions needs development!
ee. Use to analyse contact resistance

65. *Surface photovoltage*

d. Carrier concentration; R_0A
r. We have used optical scanning technique in conjunction with electrical contacts to see photovoltaic and photoconductivity response
dd. Not yet developed for MCT; requires contacts on samples
ii. Carrier type changes (inhomogeneity)

66. *Thermal wave microscopy*

j. Tried, but found nothing after a casual look
m. Defect imaging

67. *Transmission electron microscopy*

f. Defect analysis and microstructural analysis
j. Key insight into materials defects
m. Dislocation density determination
n. Defects, dislocations
p. Interface structure local phases
s. Analysis of defects
t. Defect structure
v. Defect analysis
w. Precipitates, dislocation structure, interface in II–VIs
y. Defect structure
z. Defect structure
cc. High magnification defect and dislocation analysis, damage structure
dd. Imaging of structural quality of thin-film interfaces in cross section
ee. Defects, structure. Difficult to use
ff. Crystalline quality
hh. Defect quality of material interfaces

68. *X-ray fluorescence analysis*

m. Impurity determination
t. Composition

u. Not very sensitive
y. Atom %
dd. Composition measurement of large-area samples

69. *X-ray photoelectron microscopy*

f. Surface contamination on thin film profiles
l. HgCdTe material composition, impurities
p. Local device chemistry; information on films and interfaces
r. SEM in this mode gives greater sensitivity for elemental analysis
s. Analysis of impurity bonding
y. Composition
dd. Surface composition analysis; combined with sputtering can be used for comp. depth profiling, interface chemical composition

70. *Electron channelling*

d. Orientation; surface preparation
o. Orientation, near surface crystalline quality
p. Rough orientation of crystal films
s. Crystallinity of thin layers
y. Structural symmetry
z. Crystal orientation and perfection
dd. Rapid surface sensitive measurement of crystallinity (qualitative)

71. *Electron diffraction*

f. MBE growth, crystal quality and orientation
j. Essential to good MBE
p. Assume RHEED, growth monitor MBE
s. In conjunction with TEM for analysis of defects
t. Lattice spacing, crystallinity
u. Crystalline quality, orientation, Burger's vector
y. Order/disorder
dd. Useful in high-vacuum environments such as MBE
ff. Surface perfection in MBE

72. *Surface topography: optical interferometry, stylus, scanning tunnelling microscopy*

d. Topography; defects
f. Nomarski interference microscopy, to see shallow etch pit defects
g. Thin film process measurements, grown LPE film surface morphology
j. Helps get film thicknesses, wafer depths
n. Uniformity
p. Topography to calibrate film thickness, roughness, device structures, depth analysis craters, atomic resolution structure, electronics of surface and interface, epi films, non-destructive device testing
r. Make interferometric topographs. May use to measure thickness of films by looking at bevelled edge of multilayer structure, and detecting transitions by phase change
s. Measurement of surface topography, height and period
w. Wafer flatness
y. Roughness at various levels of scrutiny to atomic resolution
cc. Surface flatness of substrates
dd. Fizeau—flatness; Stylus—etch depths, surface roughness, etc; STM—not widely used in MCT (need clean surfaces)
ff. Film thickness; stress from bow measurement

Appendix 3. Results from questions asked

In this appendix we tabulate the answers given by the respondents to four questions asked. Again each letter of the alphabet refers to a specific respondent throughout this appendix, as in appendix 2.

Questions

1. **What are the most important (2–4) properties or parameters to measure or determine? Why?**

a. Bandgap, carrier concentration, Hall mobility, dislocation density, lifetime

c. Carrier concentration, λ_c, uniformity, charge storage

d. Cut-off/composition, carrier concentration, lifetime, R_0A

e. Diode I–V, Hall, spectral response

f. Voltage past threshold (breakdown voltage), storage time, cut-off wavelength, Hall carrier concentration and mobility, dislocation density. MIS performance

g. Where are the leakage currents? Surface or bulk? Are they localized defect: Substrate related?
Properties of the individual layers of heterostructure material

h. $Hg_{1-x}Cd_xTe$ alloy composition, carrier concentration, carrier lifetimes, carrier mobilities. These *directly* determine device performance

i. Composition and composition variations on surface and in depth; same for carrier concentration and mobilities; transport properties of minority carriers; deep levels

j. Nature of point defects, spatially resolved extended defects, spatially resolved surface/interface flaws. These are the perceived causes of non-ideal device behaviour

k. • composition (absolute and variation)—governs $\Delta\lambda$ of arrays—D^* uniformity (*a*) bulk, (*b*) epilayers. *NON-DESTRUCTIVE
• non-destructive defect mapping—Te ppts, dislocations, mosaic substructure
• quick-check predictor of responsivity and detectivity on relatively unprocessed substrates

l. Hard to choose

m. X-value, n, p, μ—screen material for processing; minority carrier lifetime

n. Mobility—crystal perfection and purity; minority carrier lifetime—same as above; tellurium second phase—*ALL* MCT materials are plagued with tellurium as a second-phase problem

o. Composition, carrier concentration, junction position (diodes), crystalline quality and minority carrier lifetime

p. Materials—crystal quality, defect concentration, carrier concentration, profile of impurities and activity. Interface/surface structure chemistry and electronic property
Device—QE, R_0A, lifetime, carrier concentration and profile, D^*

r. Depends on the use. Substrates: crystalline perfection, trace element analysis; HgCdTe films: X-value, mobility

s. Composition (cut-off wavelength), carrier concentration, lifetime, dopant profiles. Most fundamental to operation of IR detector

t. Minority carrier lifetime, N_A, N_D—directly affect device performance. Lifetime good indicator of material quality
Dislocation density, electrically active defects, Te precipitates
Surface state density (MIS): I–V characteristics, quantum efficiency

u. Carrier concentration, mobility, lifetime, composition, crystalline defects concentration. If we know these values accurately, then we can predict the performance. These parameters uniquely determine the quality of the material

v. For screening MCT material: spectral cut-off, carrier concentration, mobility, lifetime
For improving MCT material: defect levels (dislocations, etc), dopant uniformity

w. Breakdown field, carrier concentration, lifetime, cut-off wavelength, dark current—these five properties determine detector performance. Need non-destructive means for mapping HgCdTe wafers for uniformity of these five properties

x. Electrical transport (Hall), composition (transmission), crystallinity (x-ray)

y. (1) Stoichiometry, (2) trace impurities, (3) oxidation state, (4) dislocation density, (5) most important—atomic structural order at surfaces and at interfaces

z. Defect structure and purity—strongest influence on device performance

bb. Composition, grading, thickness and Hall coefficient and mobility

cc. (1) Impurity content in Cd, Zn, Te and Se starting materials—must control these or have no chance for downstream quality. (2) Impurities in substrates—must control as in (1). (3) EPDs—must control in order to assume epilayer quality yields. (4) Precipitate type, size and distribution—somehow affects epilayer and device quality and yield

dd. (1) Absolute composition and compositional uniformity—determines wavelength cut-off; strongly affects device quality. (2) Carrier concentration and mobility—strongly affects device properties; control of carrier concentration is essential. (3) Minority carrier lifetime—directly affects device quality

ff. Carrier concentration, cut-off wavelength,

minority carrier lifetime, dark current—they are the factors which most directly affect device performance

gg. Composition, carrier concentration, lifetime, deep-level defects and their spatial distribution

hh. ● Diode/MIS dark current—depends on lifetime, bandgap states, surface passivation

● Diode/MIS breakdown voltage—depends on doping concentration, density and position of bandgap states

● Diode/MIS 1/f noise—depends entirely on surface passivation

ii. Composition, carrier concentration, material defects—these material properties determine the device performance

2. What measurement techniques most need to be developed, enhanced or improved? Why?

a. Imaging SIMS, defect etching

c. C–V, c–t, Hall effect, FTS

d. ● Optical probing (OMA, PL, thickness mapping by absorption—non-destructive, fast and cheap, one set-up, large area

● Detailed morphology mapping/pattern recognition—present R&D, future process control

f. Position annihilation—its limits and usefulness are not understood very well. It could provide a means for measuring defects which we have difficulty in observing (i.e., Te vacancy concentration in HgCdTe, CdZnTe, etc)

Photoluminescence—We do not have sufficient understanding of what point defects or impurities contribute to which peaks

● Non-destructive, non-contact, screening techniques

● Non-contact MIS; fast qualification of production materials

● Current MIS device fabrication takes too long

g. ● Ability to determine junction location versus alloy composition for heterostructure material—potentially a combination of cold stage Ebic in a SEM

● Wafer level screening techniques for junction quality—OMA response time (at low backgrounds) has potential

h. ● Non-contact measurement of junction quality (e.g., R_0A, quantum efficiency, . . .) would have enormous impact on array costs

● Junction (heterojunction) profiling techniques would greatly facilitate control and diagnostics of advanced device structures

● In situ monitoring of VPE film growth of HgCdTe multilayer devices

i. ● Characterization of multilayer structures

● Diode reverse recovery for measurement of minority carrier lifetimes on actual device

(after processing may have changed the properties of the material)

j. All spatially resolved materials analytical techniques which provide specific, interpretable information. NDE and in situ materials and device characterization follow close behind. Priorities should be set by the relevance of the technique to solving the most important problems

k. ● above; for layers f (x, y, depth) in scanning mode

● above; but correlated with device (PC and PV types) performance to permit reasonable specification of parameters and screening

● above; mobility, carriers and lifetime are commonly spec'd to prescreen for performance. $\Delta R/\Delta$ flux has been tested and found effective, but is little used

l. We badly need a cheap, reliable optical standard (detector, probably) for the 10–12 μm region

We also need better in-process characterization of our HgCdTe diodes, which are too fragile to be probed directly and also need to be measured at low T ($\sim$80 K) and low optical background

m. Non-destructive techniques would be very useful. X-ray techniques that correlate substrate defects to HgCdTe epi defects, and device performance

n. Starting material analysis—no suitable technique exists for PPB or less analysis; tellurium cluster detection and identification—in my opinion, Te clustering is the dominant cause of low detector yields

p. Non-destructive growth and device parameter measurement and control

q. Defect etches/EPD counts; defect detection (non-destructive if possible)

r. We need a way to map on pixel size level the carrier type, concentration and mobility. N-type HCT seems to have p-type micro-islands through it. We need to see these and figure a way to remove them

s. In general, techniques that are capable of mapping critical wafer properties that impact the variability of diode performance. For structural imperfections, x-ray topography and long wavelength cathodoluminescence or photoluminescence could be developed. Basic properties such as carrier concentration and lifetime also need to be mapped routinely. Another area of weakness is compositional inhomogeneities

t. Spatially scanning techniques LBIC; electrically active defects ought to be important for electro-optical devices techniques that are non-destructive and can be applied at different states of processing—this will help identify processing steps that limit performance

Surface analysis techniques—surface passivation still limits performance for many applications

u. Mapping techniques for carrier concentration need to be developed or improved.

Optical techniques utilized to probe the gap—needs to be enhanced and brought into more laboratories in industry

v. Techniques to measure dopant non-uniformities with sensitivity of 10^{14} cm^{-3}. This may be the limiting factor in charge storage in MIS devices on MCT

Non-destructive characterization of defects—needed to improve hetero-interfaces in films

w. Current/field, pulse, decay (J/E curves). Great potential for studying field dependence of dark current in HgCdTe. Shape variations in J/E curves yield strong clues about the source of the dark current

x. Low-level impurity identification ($<1 \times 10^{14}$ cm^{-3})

y. *In situ* surface chemistry (properties 1–3, Question 1, y) during wet *and* dry processing

z. Techniques to determine impurities—both qualitative and quantitative. LCMS—Laser Scanning Mass Spectroscopy—good impurity survey technique?

bb. Differential Hall effect

cc. ● Impurity analysis so that we can control trace impurities *very early* in the overall process rather than when the epilayer is characterized or the device is made and tested

● II–VI incorporated and the whole industry will significantly benefit from the development of ZCGFAAS under the now active US Army SBIR contract at VHG Labs

dd. ● Techniques for trace level impurity measurement at $<10^{15}$ cm^{-3} level. Ultimately correlate with deep level analysis and device properties

● 77 K p–n junction profiling technique—i.e., measure actual profile as opposed to SIMS, $S–R$ measurements (currently use taper-etch $C–V$ which is time-consuming)

● 77 K carrier concentration mapping (as being pursued by NIST)—will not be used routinely, but is helpful for development of materials

ee. ● It certainly would be nice to profile alloy concentration and junction location to better resolution to determine just where the junction occurs in heterostructure devices

● Anything related to device performance (defects, impurities)

ff. Non-contact techniques need to be developed/enhanced/improved to allow material screening quickly after growth and during processing. The time required to build, bond and test electrical devices hampers all aspects of material, process and device development

gg. Faraday rotation for non-destructive mapping of carrier concentration; defect mapping,

e.g., by DLTS or scanning photoluminescence; and scanning double crystal x-ray rocking curves

hh. ● Contactless techniques for determining material parameters relevant to the above device properties

● Rapid turnaround device data at 77 K for diodes/MIS devices

ii. ● Localized mapping techniques need to be developed to characterize the material. (Ideally, these techniques should be non-contact)

● Techniques need to be developed to identify microscopic material defects which may cause carrier-type inhomogeneity, compositional non-uniformity, etc.

3. Any additional helpful, constructive comments?

d. I do not think the Consortium approach will work. Best approach to long-range problems is to fund Government Labs (MIT, NIST, CNVEOL, etc) which can subcontract to industry

f. Too much weight is put on x-ray rocking curve half-width and it is not reflective of the overall crystal quality. Defect etching is much better

h. NIST should actively get involved in HgCdTe infrared detector technology, probably in the area of materials/process characterization

j. MCT analysis is a *very* tough problem. It will not be solved by the magical application of an overlooked technique. The most important questions to answer are: Why do I see what I see and what does this mean physically? These questions will have to be answered by carefully designing experiments combining (often) several analytical techniques and proper controls. The issues cannot adequately be addressed without the focused combined efforts of materials growth, test device (or structure fab) and materials and device analysis. A multi-organizational effort is highly desirable

k. ● A clearing house of data correlated to absolute (or, if secrecy requires, relative) performance parameters. Agreed measurement standards and cross-lab correlation (as was done by NATO composition exercise in 1980)

● Standardization of surface preparation and ambience during measurements is generally lacking

l. I have a feeling that there are many process-control test features used in the Si and GaAs industries which could be transferred and/or modified for use in HgCdTe processing—and some new features which should be developed for the special HgCdTe diode case where there are a lot of new things such as In bumps

s. I am unclear of the applicability of some of these techniques to MCT (such as charged particle activation analysis, deep level optical spectroscopy, etc). There is a need to develop some of these techniques so that better analyses can be made of defect states in MCT and to bring them to the point where they can be used as more routine characterization tools by the crystal grower

t. Quite often, materials characterization techniques and device characterization tools are developed separately, and very little effort is made to close the loop between materials parameters and device performance parameters

Any defect-detecting technique will show defects in HgCdTe. The trick is to isolate 'bad' defects from 'good' defects

y. Should have had a column entitled 'Relative knowledge of the technique' (i.e., knowledge possessed by person filling out form) for cases where 'don't know' is inappropriate. Last column should *not* have had the word 'by' in it (thought, at first, that you meant 'how' property is measured)

z. NIST should establish impurity characterization capability, including LSMS (not currently available in US—Brian Easton at Philips in UK has it)

cc. Correlation between EPDs and device performance are coming along well; now we have got to learn how to lower EPDs in substrates and epilayers

dd. Keep up the good work to measure fundamental properties such as E_g, N_i versus composition that NIST has already done

ff. I have been exposed to many of these techniques. I am aware that certain techniques are in use with which I have no experience, so I cannot say what key parameters are determined by every technique. There should be a middle ground of minor importance for techniques which are highly specialized and useful, but not used on an everyday basis. I would have placed magneto-absorption in this class, but instead I was forced to select 'not important' because the information it provides is more fundamental and less practical

gg. Need to improve detection limits of various analysis techniques such as SIMS, etc.

4. What measurement techniques have been inadvertently omitted from this listing?

a. Lifetime
d. Laser microscopy
f. Residual stress measurements in processed

devices; x-ray diffraction for crystal orientation; positron annihilation

h. Atomic force microscopy, scanning capacitance microscopy; quantum efficiency; contact resistance (especially important for p-type samples); contact and surface recombination velocity; far infrared transmission; variable-area photodiode test arrays; open-circuit photovoltage decay

j. Nothing strikes me offhand. The key is adequate use and *proper combination* of many of the techniques on the list. Many techniques should be applied versus temperature and magnetic field (in some cases). Spectroscopy should include spectral responses versus T. Depth and spatial profiles are very desirable for many techniques

k. Any technique requiring $>\$100$ K investment will likely be confined to occasional research and corroboration of cheaper, grosser techniques which are needed in production (my feelings after 25 years in the business)

l. ● Transmission line measurements for contact, sheet resistance (we use for p contacts on our p–n diodes)
● Variable-area-diode measurements → material optical response, diffusion (R_0A), and lateral optical collection effects, perimeter g–r effects

n. Photon backscattering

s. *In situ* measurement for MOCVD such as laser reflectance

w. Current/field, pulse, decay (J/E curves). Great potential for studying field dependence of dark current in HgCdTe. Shape variations in J/E curves yield strong clues about the source of the dark current

y. (1) Atomic force microscopy, (2) reflection high energy electron diffraction, (3) electro-chemical techniques (as done by Arthur Hubbard, Manuel Soriaga and J Stickney), (4) ADAM (Angular Distribution Auger Microscopy—*Science*, in January 1990, **247** 182–8) (by Hubbard and Doug Frank)

z. LSMS

bb. Microscopic etch pit and dislocation density

cc. None that I can cite

dd. (1) UV–NIR surface reflectance to measure surface composition from E_1 transition (comments under reflectometry). (2) X-ray topography techniques other than double-crystal (not a serious omission). (3) IR microscopy to image precipitates in substrates and layers. (4) X-ray lattice constant measurements. (5) X-ray Laue back-reflection to determine single crystal orientation; powder diffraction and other specialized techniques

ee. Imaging SIMS

ff. MIS reverse recovery lifetime, MIS storage time

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