Intense source of monochromatic electrons: Photoemission from GaAs

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Measurements of intensity and width of the energy distribution for photoemission from negative electron affinity GaAs have been made as a function of surface preparation and temperature. Energy distributions as narrow as 31 meV (full width at half-maximum) have been obtained. The measured currents are compared to those which are currently available by coupling thermionic cathodes with electron monochromators and found to be at least 10 times as intense for distributions of equivalent width.

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Electron beams are used as probes in a wide variety of experiments in surface physics, atomic and molecular physics, and solid state physics. The feasibility of these experiments and the extent to which detailed information can be extracted from them are frequently determined by the intensity and width of the energy distribution of the electron beam. Traditionally, electron beams are generated by thermionic emission where the intensity and the width of the energy distribution are both dependent on the temperature of the emitter.[1] Typical operating widths for these sources range from ~ 0.2 to 0.5 eV. Narrower distributions are produced by injecting the thermionic emission into an electron monochromator[2] which acts as a bandpass filter on the energy distribution.

Photoemission has emerged in the last decade as a means of generating electron beams,[3–9] primarily from III-V semiconductors like GaAs. These electron beams can be spin polarized with polarization ranging from 30 to 49%. Moreover, very short pulses and high currents can be obtained; currents of 60 A and current densities of 180 A/cm^2 have been observed in 2-ns pulses.[9] It is the purpose of this letter to demonstrate a property of photoemission from GaAs which should be of interest to the more general electron beam user, namely, the ability to generate intense (several μA) electron beams of narrow (< 100 meV) energy distribution. In particular, measurements of the energy distribution and total current produced by photoemission from GaAs are presented and compared to those obtained by coupling thermionic cathodes with electron monochromators.

The mechanism of photoemission from negative electron affinity (NEA) GaAs can be modeled as a three-step process[10]: (1) absorption of a photon and creation of an electron-hole pair, (2) transport of the electron through the solid and towards the surface, and (3) emission of the electron which entails passage through the surface layer and escape into the vacuum. For an electron to escape it must have an energy greater than the vacuum level. This is achieved by using a photon energy which is greater than the work function of the material. In metals, electron-electron and electron-phonon collisions during step (2) cause the electrons to lose energy (relaxation), populating normally unoccupied states all the way down to the Fermi level and reducing the number of electrons which have sufficient energy to escape. If one employs photons of an energy significantly above the work function to compensate this effect and achieve higher yields, the undesirable result obtained is that broad energy distributions are produced. However, in semiconductors like GaAs, the band gap provides a natural barrier to complete relaxation. When the photon energy is chosen to be slightly greater than the band gap, the energy distribution of photoexcited electrons becomes the thermalized distribution of electrons in the conduction-band minimum.[11] Normally, these electrons do not have sufficient energy to escape into the vacuum. However, in heavily doped p-type GaAs, application of cesium and oxygen to the surface, coupled with band bending effects of the dopant, can lower the vacuum level to below the minimum of the bulk conduction band, creating what is known as a negative electron affinity condition.[12] The levels of the conduction-band minimum and the valence-band edge as a function of distance from the surface, along with the Cs and O surface layer,[13] are shown schematically for NEA GaAs in Fig. 1, as are resultant photoemission energy distribution curves (EDC's). Factors which affect the width and shape of the EDC have been previously analyzed[11] and include such parameters as the barrier reflectivity, the temperature of the crystal, and the magnitude of the negative electron affinity. As is shown in Fig. 1, for small values of NEA the vacuum level acts as a low-energy cutoff on the electron distribution, producing narrowed EDC's.[14–16] Experimentally, one can adjust the vacuum lev-

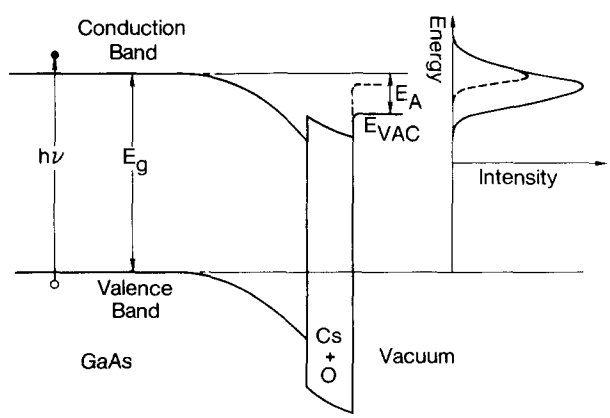

FIG. 1. Schematic representation of the energy levels of the conduction-band minimum and valence-band edge when traversing left to right from the bulk to the band bending region, through the Cs and O layer and finally into the vacuum. Two values for the vacuum level (solid lines and dashed lines) are shown along with the two EDC's that would be produced for the resultant values of NEA.

el and hence tune the width of the EDC by adjusting the Cs and O balance on the surface.[14] As a monochromatic electron source, NEA GaAs then has two important properties: (1) the photon flux can be used to control the intensity of the emission and (2) the Cs and O balance can be used to control the width of the energy distribution.

Measurements of the EDC's from NEA GaAs were performed on the NBS polarized electron scattering apparatus[3] coupled with a 135° spherical deflection electron kinetic energy[17] and polarization[18] analyzer; these instruments have been previously described in detail. A GaAlAs laser operating at 810 nm was used for the photoemission excitation. The energy analyzer was operated at a pass energy of 1.5 eV for which the analyzer resolution is calculated to be 25 meV. The total current produced by the photoemission was measured as the current leaving the cathode, which was in good agreement with an alternative measurement of total current absorbed on electron optical elements in the system, when those elements were biased to intercept the electron beam.

The goal in the experiments was to determine the electron energy distribution from the cathode at high output current. In order to avoid the intrinsic limitations of conventional spherical (cylindrical) energy analyzers, i.e., energy broadening due to the Boersch effect,[19] it was necessary to allow only a fraction of the total current to enter the energy analyzer. We changed deflection plate settings and lens focusing parameters to select representative samples of 10^{-3}–10^{-4} of the total current for analysis. The narrowest energy distributions were obtained when the electron beam current was reduced early on in the beam line eliminating the possibility of energy broadening due to the Boersch effect during transport.

The EDC's which were obtained when the Mo block which supports the GaAs crystal was maintained at 300 or 77 K are shown in Fig. 2. The measured widths (FWHM) of these curves are 100 and 40 meV, respectively. These widths are a result of convoluting the width of the cathode distribution with the analyzer resolution. When the analyzer resolution is removed, cathode distributions of 97 and 31 meV are obtained. The measured emission current for the 300-K data was 7 μA and for the 77-K data was 1 μA. The shift in the energy of the low-temeprature distribution relative to that at room temperature is a consequence of an increase in the band gap.[11] The reduction in current at 77 K is a result of a lower 810-nm photoemission yield at low temeprature.[3,14] It is believed that some of this reduction is due to freezing out of additional Cs onto the cathode. We further believe that these currents represent lower limits to what is possible and could be increased with a more intense light source. Further work is necessary to test the feasibility of obtaining higher currents while still maintaining the narrow width of the energy distribution during transport by the electron optics. With careful design, it is possible to minimize electron beam stimulated desorption of ions and neutrals (from electron optical elements) which return to and decrease the lifetime of the photocathode. Photocathodes have been demonstrated[20] to be capable of producing 250 μA of continuous current for up to 10 h with little loss in intensity. The cathode is easily rejuvenated in a few minutes by adding a small amount of Cs.

Measurements have also been made of the polarization of the energy analyzed photocurrent, details of which will be discussed elsewhere.[14] The measured polarizations were found to be independent of energy distribution width and emission current and consistent with our previous determination.[3]

As can be seen in Fig. 3, where these data are compared with those obtained by coupling thermionic cathodes with electron monochromators,[21–26] the measured direct emission from NEA GaAs is at least 10 times as intense as the largest currents of equivalent energy width that are currently available from electron monochromators. Whether this

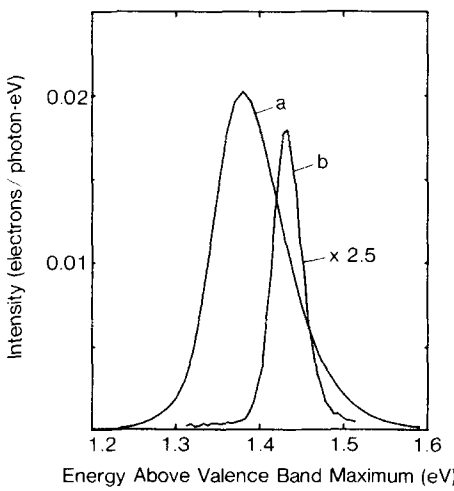

FIG. 2. EDC's which are obtained with the Mo sample holder maintained at (a) room temperature and (b) liquid N_2 temperature. Each curve is normalized by setting the area under the energy distribution equal to the quantum yield.

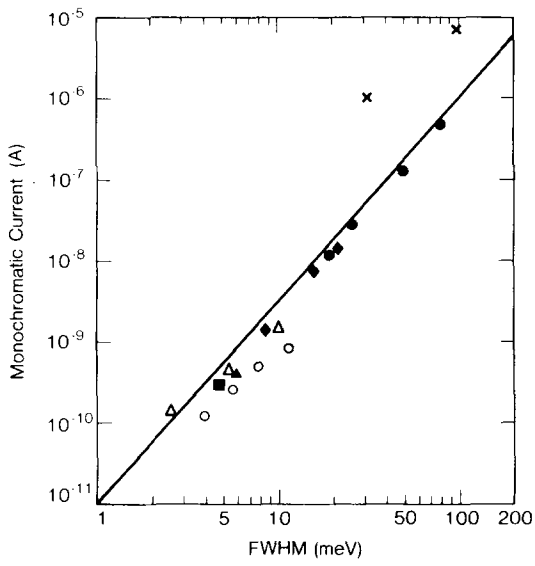

FIG. 3. Cathode current and distribution width of the EDC's obtained from photoemission from NEA GaAs (×) are shown compared to that available by coupling thermionic cathodes with electron monochromators. The data points which are shown as solid symbols are from systems using spherical deflector monochromators, while those shown as open symbols come from systems using cylindrical deflector monochromators. The solid line follows $I\alpha(\Delta E)^{5/2}$, see Ref. 21. These data obtained from: (×) this work, photoemission from NEA GaAs; (●) Kuyatt and Simpson, see Ref. 21; (◆) Swanson, see Ref. 22; (▲) Demuth, see Ref. 23; (■) Avery, see Ref. 24; (○) Ibach and Mills, see Ref. 25; and (△) Kesmodel, see Ref. 26.

level of performance can be extended to distributions which are further narrowed by coupling a NEA GaAs photocathode with an electron monochromator is as yet undetermined and warrants investigation.

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