MEASUREMENT OF PATTERNED FILM LINEWIDTH FOR INTERCONNECT CHARACTERIZATION

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Abstract — Test results from high-quality electrical and physical measurements on the same cross-bridge resistor test structure with approximately vertical sidewalls have shown differences in linewidth as great as 90 nm for selected conductive films. These differences were independent of design linewidth. As dimensions become smaller, the accurate measurement of the patterned conductor width is necessary to assure predictable timing performance of the interconnect system as well as control of critical device parameters.

INTRODUCTION

As interconnect dimensions are scaled down, RC delay becomes a serious performance issue, especially at high frequencies. By the year 2001, line-to-line pitches for advanced semiconductor interconnect systems are planned to be approximately 0.55 μm [1]. Considerable effort is underway to develop new materials to reduce both the interconnect line resistivity and the dielectric constant of interlayer dielectrics. In addition to these factors, both the length and width of the conductive interconnect line are important in determining the propagation delay between circuit elements.

In order to assure process control for the designed circuit performance, accurate and precise measurement of interconnect linewidth becomes increasingly critical. Increasing concern has arisen concerning apparent differences in the measurement of linewidth using electrical and physical techniques (e.g., as measured by optical microscopy, scanning electron microscopy (SEM), scanning tunneling microscopy (STM), or atomic force microscopy (AFM)). In order to address these concerns, several test chips have been developed to allow measurement comparison between these methods. This work mainly focuses on recent comparisons of dimensional measurements using an electrical measurement system, a high-accuracy coordinate metrology system, known as the NIST Molecular Measuring Machine (M^3) [2], and a high-quality optical microscope.

LINEWIDTH DEFINITION AND MEASUREMENT

The width of a conducting path is one of the critical measurements in semiconductor metrology. Currently, there are two classes of tools that provide these measurements: electrical and physical. While the electrical linewidth is relatively fast and easy to determine, it conceptually differs from the physical linewidth. Both measurement techniques should provide the same results for ideal samples with vertical edges, uniform thickness, and uniform spatial electrical conductivity.

The electrical width is defined as *the effective conductive path width of a patterned, uniform conducting film whose length is typically much larger than its width.* While the measurement of the electrical linewidth is affected by the slope and edge roughness of the line edge, the final measurement is extremely repeatable; that is, repeated measurements of the same line segment results in the same value of electrical linewidth.

The physical width of a line is conventionally related to the distance between two defined points in the output signal of the respective instrument, e.g., the 27% transmission point at both edges of the image of a line using Köhler illumination in an optical microscope [3]. For optical microscope and SEM measurements, the output signals are usually derived from an averaging of a 1-μm-or-less segment length of the line. Each line scan of an STM or AFM samples a segment of 1 to 10 nm. However, images built from line scans extending over tens of micrometers to millimeters in length can be obtained by multiple scanning with the M^3. Relating these instrument output signals back to the physical geometry of the material line requires extensive modeling of the interactions of the test probe with the line/substrate materials. Careful modeling is difficult when the dimensions of the line become comparable to the characteristic dimensions of the test probe, i.e., wavelength of light for the optical microscope, bloom size for the SEM, and probe radii for the STMs. Sloped edges of the line and roughness of the edge along the line further complicate the modeling. Consequently, the repeatability of physical measurements of lines with rough edges is dependent on the repeatability of the position and length of the line segment sampled.

One key difference between the two classes of techniques, i.e., electrical and physical, is that both the physical characteristic being measured and the definition of linewidth are different. The electrical width averages the entire conducting path of the line being measured, while the physical width is obtained from "slices" of the line. These slices may include regions of lower electrical conductivity which are not completely reflected when interpreting the electrical measurement. The physical linewidth measurement may not correctly account for a nonuniform and/or nonrectangular cross section; the "classical" physical definition of linewidth presupposes uniform, rectangular features. Defining a feature with a nonrectangular cross section to have a single-valued linewidth related to the meter may not be terribly meaningful for patterned semiconductor films.

An additional difference between the electrical and physical techniques is due to the different methods of calibrating the measurement instrument. For physical techniques, linewidth measurement accuracy depends on the calibration of the measurement device to the ISO definition of the meter. For electrical techniques, electrical linewidth measurement accuracy (assuming that the measurement instruments are linear) depends primarily upon the calibration of the primary writing instrument which defined the length of the conductive, line comprising the bridge resistor.

Electrical Measurement

Electrical measurements were obtained using a commercially available parametric test system with nanovolt and picoampere resolution. For the electrical measurements, the electrical characterization of linewidth, w, involves measurement of bridge resistance, $R = \rho \times L/(w \times t)$, where ρ is the film resistivity, L is the length, and t is the thickness, and sheet resistance, $R_s = \rho / t$ [3]. The resistivity is assumed to be the same in the bridge and the cross.

Electrical measurement precision was determined to be 2.0 nm (3 sigma) based on approximately 1000 repeated measurements of one cross-bridge resistor test structure with a nominal 1.0-μm design linewidth. Electrical linewidth measurement uncertainty was determined to have an upper limit of approximately 10 nm for the current and voltage ranges used. To prevent significant joule heating, the linear (i.e., ohmic) range of applied current and the measured voltage was determined, and the measurement current chosen from within this range. The average measurement time of a cross-bridge resistor is less than 1 s. For this work, the overall design of the cross-bridge resistors conformed to design rules found elsewhere [4].

Physical Measurement

The NIST Molecular Measuring Machine (M^3) is a two-dimensional, coordinate-measuring machine conceived and designed to extend the state of the art of the world's dimensional measurement capabilities. It is designed to have a planar measurement range of 50 by 50 mm, while accommodating surface height variations of as much as 100 µm. The probe is a scanning tunneling microscope, which gives an imaging resolution that extends to the atomic scale. The displacements are measured with a state-of-the-art, heterodyne interferometer having a measurement resolution of 0.075 nm with a 2-kHz bandwidth. The measurement system uncertainty, including the effect of the uncertainty in the tip diameter is estimated to be ±10 nm. The design goal is for a total uncertainty of 1 nm over the full measurement volume. These metrological goals have also necessitated state-of-the-art temperature control of ±0.1 mK and advanced isolation from seismic and acoustic disturbances.

After coating test samples with a thin, conductive gold film (~10-nm thickness), the sample is placed on a stage and scanned by the STM probe. An image is obtained with each pixel's location being referenced to the coordinate metrology system. As is discussed later, the uncertainty of the linewidth measurements on the aluminum line samples was estimated to be less than ±40 nm. A further description of this system can be found elsewhere [5].

Optical Measurement

Optical measurements were made using a transmission optical microscope with an objective lens of 0.9 numerical aperture set up for Köhler illumination using partially coherent light from a filtered incandescent source at 530-nm wavelength. A further description of this system and the measurement method can be found elsewhere [3]. For the samples tested, optical measurement repeatability was determined to be approximately 10 nm. The expanded uncertainty, traceable to international standards for the definition of the meter, was determined to be approximately ±45 nm for the samples tested.

EXPERIMENT

In order to allow comparisons between electrical and physical characterizations, three test chips similar in design were fabricated for this experiment. All test chips contained cross-bridge resistor test structures with bridge design widths of 0.2 to 2.0 µm. Patterning was performed by using a direct wafer stepper to expose a photoresist layer. A more detailed description of the three test samples is found in Table 1. In two of the samples, transparent quartz substrates were used in order to allow comparisons of transmitted-light optical linewidth measurements with electrical measurements for the same line segment.

Table 1 Test Sample and Processing Description

Sample	Film	Design Film Thickness, nm	Substrate	Etch
A	Chrome	100	quartz	wet
B	Titanium	100	quartz	dry (RIE)
C	Aluminum	1000	SiO_2 on Si	dry (RIE)

RESULTS AND DISCUSSION

Figure 1 shows results from both transmitted-light optical and electrical linewidth measurements of cross-bridge resistors for patterned chrome samples (Sample A). The measurements are for the same set of samples. The results seen in Figure 1 show a difference of approximately 65 nm in measured linewidth over the ranges measured. Similar results, seen in Figure 2, show that, for patterned titanium films on quartz substrates (Sample B), there is a systematic difference of approximately 90 nm between optical and electrical measurements [6]. This difference is larger than can be reconciled, considering both the slope of the line edges, as determined by SEM inspection, and the uncertainties of the respective measurement systems.

Figure 3 shows an M^3 image of Sample C. This illustration represents 50 line profiles or scans spaced 100 nm apart. The conditions under which the profiles were obtained are found in Table 2. The average thickness of the measured line was approximately 750 nm. The linewidth of the image at 85% of this average thickness was determined to be 795 ± 40 nm. The overall uncertainty of the measurement is considered to be a combination of the line edge roughness and measurement tool uncertainty. From the image, the estimated sidewall angle of the line was

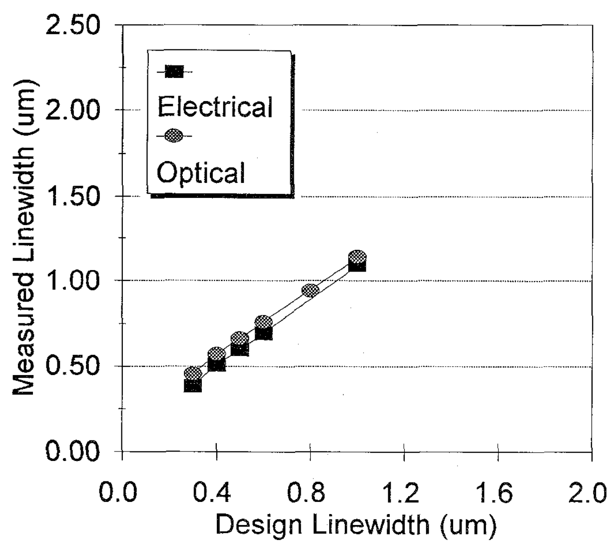

Fig 1. Electrical and optical measurements for chrome-on-quartz sample (Sample A).

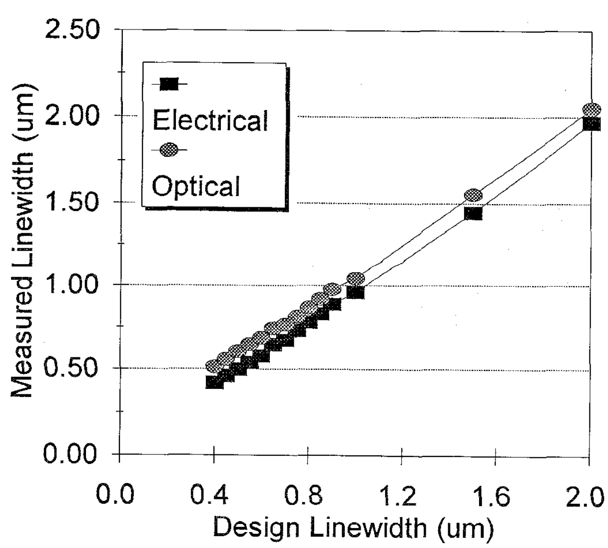

Fig 2. Electrical and optical measurements for titanium-on quartz sample (Sample B).

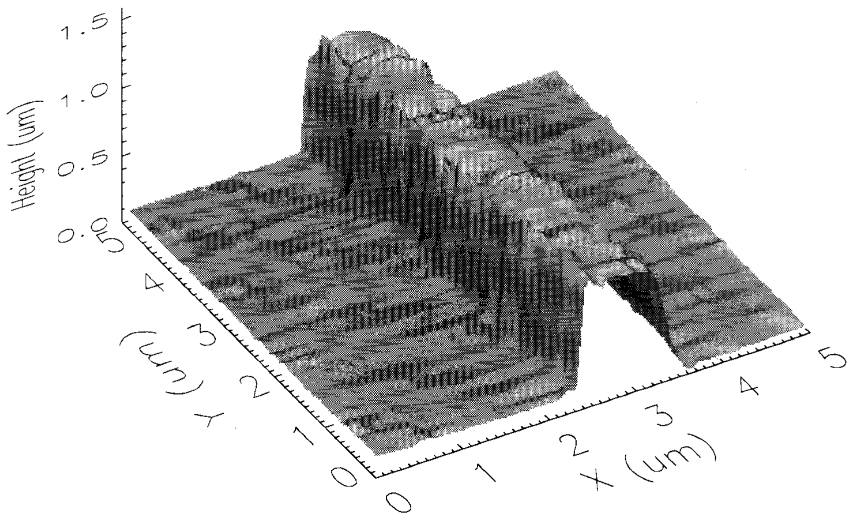

Fig 3. M^3 scanned image of an aluminum-on-silicon sample. The line thickness is approximately 750 nm. As with all STM systems, the image is a convolution of the probe tip and the positional information reflects piezo hysteresis and tip bending effects.

Table 2 Scan Parameters for M^3

Tunnel current	0.5 nA
Tunnel bias	0.25 V
Scan speed	100 nm/s

Table 3 Approximate Measurement Differences, nm

Sample	Film	Electrical-Optical	Electrical-M^3
A	Chrome	65	
B	Titanium	90	
C	Aluminum		-5

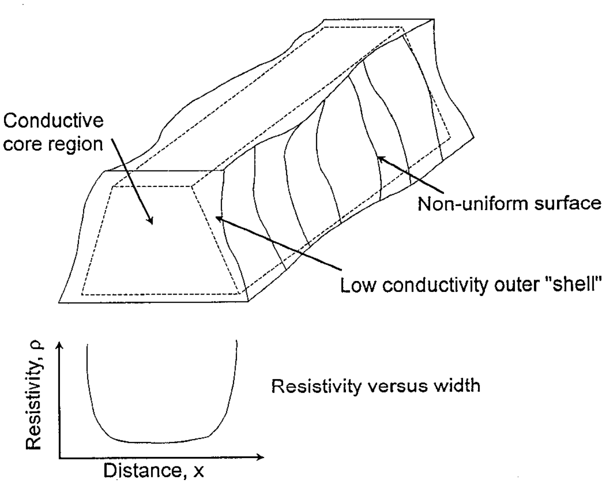

Fig 4. An example cross section of a line sample showing trapezoid cross section and the effective resistivity of the conductive core.

≥86°. Accounting for this sidewall slope, the estimated tip diameter (approximately 40 nm), and the gold film overcoat, the width of the structure at mid thickness is determined to be 830 nm. This can be compared to the measured electrical linewidth for this sample of 835 nm.

While at the resolution limit of physical linewidth metrology, the results from the chrome and titanium samples suggest that an offset exists between electrical and physical linewidth measurements and that the electrical linewidth is always smaller than the physical linewidth. Results from the aluminum samples suggest that any differences are well within the respective uncertainties of both measurement systems. Based on the approximately constant linewidth offset between design linewidth and measured linewidth for both chrome and titanium samples, seen in Table 3, a measurement interaction at the edge of these samples is suggested and the interaction is a function of the material type.

Sheet resistance measurements, using the van der Pauw resistor, are largely independent of line-edge quality. Most designs are either "edgeless" (i.e., two intersecting lines) or contain a large square of uniformly conductive material and have been shown to provide repeatable estimates of sheet resistance for a variety of design dimensions [7][8].

For the bridge resistor, the actual resistivity, ρ, can be is considered to be a function of the proximity to the edges. In a schematic cross section, illustrated in Figure 4, the resistivity versus width is represented by a U-shape behavior, with a central core characterized by the bulk resistivity, and the edge regions near each wall with higher resistivity values. This is also influenced by the stress distribution in narrow metallization lines [9].

For the samples considered in this work, the primary factors that can affect the final determination of linewidth measurement are:

> Linewidth Definition — The SEMI definition of linewidth [10] states "*... at a given cross section of the line, the distance between the air-line material boundaries at some specified height above the interface between the patterned layer in which the line is formed and the underlying layer*" and "*... substantive method dependent differences in measurement results may be expected and it is convenient to identify the*

method used in expressions such as 'SEM linewidth,' 'optical linewidth,' or 'electrical linewidth.'" Hence, even when a line is geometrically symmetric, uniform along its length, and physically and chemically spatially uniform, substantial method-dependent differences in measurements made by different techniques *may be expected* as a result of arbitrary height selection. In practice, departures from line uniformity are common and amplify measurement differences.

Line-Edge Roughness — Figure 3 shows an image of the overall roughness of an sample edge. This sample is typical of films that can be encountered in semiconductor devices. As the side walls of the sample become more jagged, both the electrical and physical measurements will be affected. For the electrical measurement, the effective conductive path width will be reduced, resulting in an effective narrower line. Physical measurements will become more complex as a series of averages have to be made in order to determine the effective average physical linewidth.

Edge Passivation — During the patterning process, the electrical conductivity at the edges of the lines may be degraded. Physical causes for this reduced edge conduction are the formation of a non- or low-conductive layer at the edges caused by a reaction between the etchant species used to pattern the film and the film itself.

Scattering — The effect of localized wall damage on resistivity is linked to the relative size of the electron-mean-free path in the metal. A simple calculation, based on the Sommerfeld theory of metallic conduction [11], shows that at room temperature the electron-mean-free path for the metal used increases in the order: titanium, chromium, aluminum, and gold. The values are, respectively: 0.7 nm, 1.5 nm, 15 nm, and 34 nm. For identical submicrometer-size line geometry, unpassivated lines fabricated with these pure metals are expected to show a difference between optical and electrical linewidths. This difference is higher with titanium, and becomes increasingly smaller with chromium, aluminum, and gold. For a given defect size, the electron-defect scattering probability is expected to increase inversely with the electron-mean-free path.

SUMMARY

The metrology process used in manufacturing advanced semiconductor products must provide accurate, precise, fast, and cost-effective measurement results. In order to characterize key performance parameters of such products (e.g., the timing of submicrometer interconnect systems), the *electrical* performance of the products must be specified and controlled. Electrical measurements represent the only metrology that properly reflect the end properties that need to be controlled for fabrication-process and product-performance-assurance purposes.

In order to assure correct process metrology for instances where electrical metrology tools cannot be used or for other instances when physical tools are inadequate, the relationship of the electrical linewidth to physical linewidth must be understood. In both cases, the accuracy of both techniques must be determined and comparisons made, and the definition and interpretation of linewidth must be clearly understood.

This work has shown measurable differences between electrical linewidth and physical linewidth for selected, patterned conductive films. Differences greater than 15% have been measured for a 0.5-μm line. For advanced semiconductor products, the effective conductive electrical path width of interconnect lines may no longer scale linearly with lithography. Accurate comparisons between these two measurements are currently at the limits of state-of-the-art physical metrology systems which are on the order of ±40 nm.

This work is a part of an ongoing research project to compare the accuracy of electrical linewidth measurements with physical linewidth measurements and to identify physical causes for measured differences. A goal of this effort is to study the relationships between all the physical techniques for deducing line geometry and the effective conductive path geometry deduced from electrical linewidth measurements. Additional efforts are underway to evaluate linewidth measurements for patterned doped polysilicon films, for gold films with sub-0.2 μm features, and for single-crystal silicon films.

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