PHOTOTHERMAL MEASUREMENT OF METAL FILM THICKNESS IN INTEGRATED CIRCUIT DEVICES

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INTRODUCTION

Metal films have been used extensively in very-large-scale integration (VLSI) devices. They are used to build interconnects, field-effect transistor gates, diffusion barriers, and conduction pads for input or output leads. Metals such as aluminum, tungsten, titanium and platinum are deposited on an insulating layer [1,2]. The metal film thicknesses range from 100 Å to 1 μm . Due to the ever-growing need for high speed, high density, and low power dissipation in integrated circuit (IC) technology, accurate control of the metallization process becomes essential to ensure the quality and yield of the final product. One of the important parameters in the metallization process control is the film thickness.

Unlike transparent films, which can be measured by many optical techniques such as ellipsometry or spectrometry, metal films are opaque to light. Most of the techniques, the surface resistivity method and electron microscopy for example, used in the IC industry, require either physical contacts to a wafer or lapping a wafer for cross-sectioning. With these techniques, following a measurement, because of contamination, the wafer cannot be placed back on a production line, and the measurement is slow and expensive. Therefore, there is a need for a noncontacting and nondestructive technique to measure metal film thicknesses in integrated circuit devices.

It is known that thermal waves can be used to depth-profile sample structures [3,4]. The thickness of a thin film can be measured nondestructively from the modulation amplitude of either thermal wave induced surface reflectance change [5], laser beam deflection [6], or the "mirage" effect [7]. Using the amplitude of the photothermal signal has the advantage of a large dynamic range. However, the accuracy of measurement depends on its amplitude calibration. Instability of optical alignment, changes in sample surface roughness, or sample tilt can cause an error in an amplitude measurement. It is very difficult to calibrate for all the factors to ensure the accuracy of a thickness measurement. Therefore, we have chosen to measure the phase change of the thermal wave.

For this purpose, we have developed a new, high-frequency, noncontacting, and nondestructive photothermal phase microscope to measure opaque film thicknesses. In VLSI devices, metal films are usually deposited on top of an insulating layer (a poor thermal conductor). The thickness of the insulating layer is typically a few thousand Ångstroms and is made of silicon dioxide, fused silica, or fused quartz. For simplicity, in the rest of the discussion, we assume that

the insulating layer is made of silicon dioxide. We focus an intensity modulated heating laser beam with a microscope objective to a focal point on the film surface (see Fig. 1). The periodic laser heating introduces temperature variations at the focal point and excites a thermal diffusion wave. When the metal film is thermally thin, the existence of the metal-insulator interface affects both the amplitude and phase of the surface temperature variation with respect to the heating beam modulation. Using the fact that the optical reflectance of metals changes weakly with temperature [8-10], the surface temperature variation is detected by a second focused probe laser beam.

In order to measure a metal film thickness ranging from 100 Å to 1 micron, the intensity of the focused heating laser beam is modulated at frequencies up to 500 MHz. The phase delay between the surface temperature variation and the heating beam modulation yields the thickness of the opaque film. Phase measurements of aluminum, tungsten, titanium and TiW alloy films have proven that the phase information of the photothermal signal indeed can be used to determine opaque film thicknesses in VLSI devices with high repeatability. A major advantage of using phase instead of amplitude of the photothermal signal is that the thickness measurement is independent of amplitude calibration.

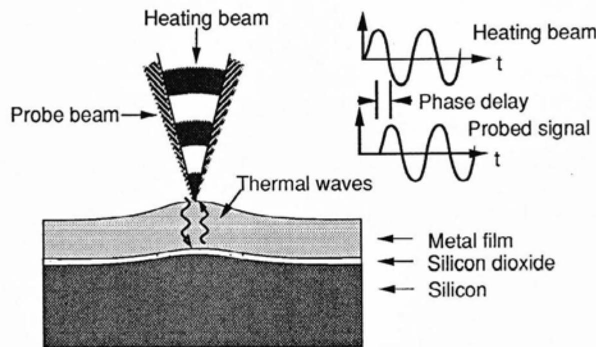

Fig. 1. Schematics of photothermal phase measurement of a metal film in VLSI devices.

THEORY

High frequency excitation, where the thermal wavelength is comparable to the film thickness, must be used to maximize the range of phase variation with the film thickness of the photothermal signal. For thin films, the diffusion length of the thermal wave is then comparable to or less than the spot size of the heating beam, and the diffusion is essentially in the vertical direction into the film instead of in the radial direction along the surface of the film. Therefore, the thermal wave behaves as if it is one dimensional. On the other hand, for amplitude measurements, lower frequencies, where the diffusion length is much larger than the laser spot size, are used. In this case, the illuminating beam behaves like a point source and the thickness of the film now determines the rate of heat diffusion in the radial direction. Thus, under these conditions, the amplitude of the surface temperature variation is a strong function of film thickness.

In the one-dimensional case, the temperature distribution and time dependence are governed by the thermal diffusion equation:

$$\frac{\partial^2 T}{\partial x^2} = \frac{\rho C}{\kappa}\frac{\partial T}{\partial t}, \tag{1}$$

where T is the temperature at position x at time t, ρ is the density, C is the specific heat, and κ is the thermal conductivity of the medium. Equation (1) has the general solution:

$$T(x,t) = Ae^{-(1+j)x\sqrt{\omega/2D}}e^{j\omega t} + Be^{(1+j)x\sqrt{\omega/2D}}e^{j\omega t}, \tag{2}$$

where A and B are constants, and $D = \rho C/\kappa$ is the diffusivity of the medium.

For frequencies higher than 1 MHz , it is safe to assume that the insulating silicon dioxide layer under the metal film is thermally thick, and that there is no reflected thermal wave in the oxide. Assuming planar surface heating, the solution for the surface temperature variation has the form:

$$T(0,t) = \frac{J_0 e^{-\pi/4j}}{\sqrt{\omega\kappa\rho C}}\frac{1+Re^{-2(1+j)h/\mu}}{1-Re^{-2(1+j)h/\mu}}e^{j\omega t}, \tag{3}$$

where h is the thickness of the film, ω is the angular frequency of the thermal wave, $\mu = \sqrt{2D/\omega}$ is the diffusion length of the thermal wave in the metal, $R = (B/A)\exp^{2(1+j)h/\mu}$ is the reflectivity of the thermal wave at the metal-oxide interface, and J_0 is the absorbed power per unit area of the heating laser.

The phase delay of the surface temperature variation with respect to the heating beam modulation depends only on the film thickness and material properties of the film and the oxide. It does not depend on J_0, which is subject to change by drifts in beam alignment, changes in wafer surface roughness, or wafer tilt. As long as the film and oxide properties are known, the phase of the photothermal signal can be used to determine the thickness of an opaque film.

When a film is thermally thin, i.e., $h/\mu \ll 1$, the phase lag of the surface temperature variation is linearly proportional to the film thickness:

$$\phi = -\frac{4R}{1-R^2}\frac{h}{\mu} - \frac{\pi}{4}. \tag{4}$$

When the heating source is a circular spot of finite diameter, the diffusion equation must be solved in a cylindrical coordinate system. The resulting phase lag of the surface temperature is smaller than, but varies with, h in a similar way to the one-dimensional case. At very low frequencies, the phase lag ϕ approaches zero instead of the $-\pi/4$ predicted by the one-dimensional theory.

Figure 2 shows the theoretical phase responses of the surface temperature variation at the center of the heating laser spot for titanium films deposited on silicon dioxide. We have assumed that the heating is only on the surface of the film. The heating source is assumed to have a Gaussian intensity distribution with a full width at half maximum (FWHM) of 1.0 micron. The films are thermally thin (in titanium, for example, a thermal wave of 40 MHz has a diffusion length of 2700 Å). As can be seen from the plot, films with different thicknesses have a different phase lag. There is a fairly large dynamic range in phase at high frequencies.

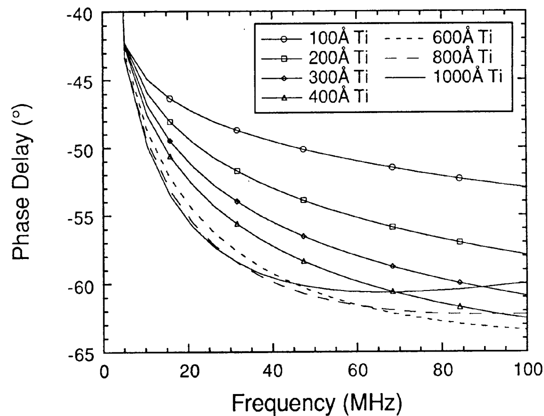

Fig. 2. Three-dimensional theoretical simulation of phase lag of surface temperature variation with respect to the heating beam modulation of titanium films on SiO_2.

EXPERIMENTAL APPARATUS

In order to measure metal film thicknesses in VLSI devices, we excite thermal waves at frequencies from 1-500 MHz. At frequencies greater than a few MHz, capacitive loading dominates unless the detector is terminated with a low impedance. In this case, the noise level is determined by the input amplifier. However, at low frequencies, it is normally possible to obtain much greater sensitivity and shot-noise-limited operation by working into a high impedance. Thus, to achieve a high sensitivity detection, we chose to modulate both heating and probe laser intensities at high frequencies which differ by a relatively low frequency, 92 kHz. Since the photothermal signal is the product of the probe beam intensity and the temperature variation at the probe beam spot, the photothermal signal in the reflected probe beam is optically mixed down to the differential frequency at the sample surface. We use a conventional lock-in amplifier to achieve narrowband detection. More importantly, downshifting the signal frequency allows us to take the advantage of high impedance detection electronics to achieve the needed sensitivity.

Figure 3 is a schematic of the photothermal phase microscope. The heating beam laser and probe beam laser, emitted by an 830 nm and a 789 nm diode laser, respectively, are collinearly combined with a lowpass dichroic mirror and focused to the surface of a sample.

Two pairs of prisms circularize the laser beam shapes, and a 0.9 NA microscope objective focuses beams to a spot size of 1.0 micron. Extreme care is given to the collimation of the laser beams to minimize the astigmatism of diode lasers. A 1/4 waveplate and beamsplitters are used to attenuate reflections back to the laser diodes to reduce reflection induced noise. The arrows and dots in the schematic indicate directions of the laser polarization. A polarizing beamsplitter selects the reflected probe beam to a photodiode and the photocurrent is measured with a lock-in amplifier.

The 830 nm heating laser has an average output power of 15 mW. Due to power losses along the path, and the high reflectivity of metals, the absorbed heating laser power is only about 0.3 mW at the heated spot. The intensity of the probe beam is ten times weaker than the heating beam. The total heating effect of the two lasers yields a dc temperature rise of less than 20°C. Therefore, the measurement is truly nondestructive to the sample.

In addition to the basic optics for photothermal measurements, a tungsten lamp is added to illuminate the sample surface, as in a normal microscope. A CCD camera and a TV monitor display a microscopic image of the sample and the laser spots so that we can locate the beams at a designated position.

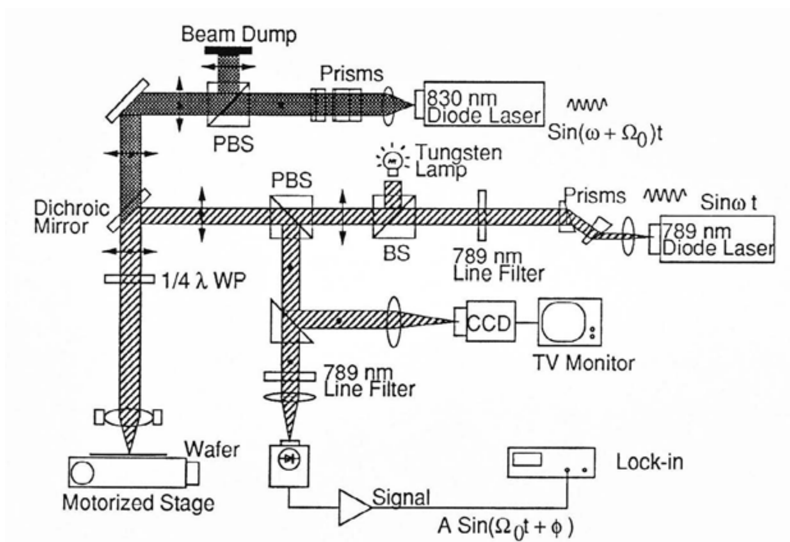

Fig. 3. Optical set-up of the photothermal phase microscope.

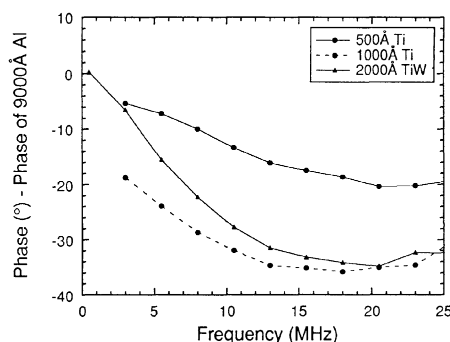

Fig. 4. Phase measurement of the photothermal signal of a 500 Å and a 1000 Å titanium film, and a 2000 Å titanium-tungsten alloy film on oxide. The vertical axis is the difference of the phase measured off a film and that off a reference sample (a 9000 Å aluminum film on oxide).

There are many advantages in using diode lasers in the set-up. It is very easy to modulate a diode laser up to hundreds of megahertz by simply modulating its driving current. We have succeeded in detecting photothermal signals at frequencies up to 500 MHz . This allows us to measure metal films in the range of a few hundred Ångstroms in thickness. Secondly, diode lasers are very quiet so that we can achieve shot-noise-limited detection of very weak photothermal signals [$(1/R)dR/dT$ is on the order of 10^{-5}-10^{-4}/°C] [10]. Moreover, diode lasers have extremely good pointing stability. This is crucial because a drift as small as 0.25 micron of either beam can reduce the signal amplitude and cause unwanted noise and errors in the phase measurement. The outstanding pointing stability of diode lasers simplifies the alignment of the optics largely and ensures the stability of the system.

RESULTS AND DISCUSSION

Measurements have been made of various films types of different thicknesses. The total phase delay measured consists of a phase delay due to the thermal wave and a constant phase delay in the electronics. In order to cancel out the instrumental phase delay, we take the difference between the phase measurement of a film and that of a reference sample. The reference sample can be a thick film or even a polished metal plate to ensure that there are few or no reflected thermal waves from the bottom surface. Ideally, the photothermal phase delay is $-\pi/4$ when the reference is thermally thick. For the data shown in this paper, the reference sample is chosen to be a 9000 Å aluminum film on silicon dioxide. Although it is only thermally thick for frequencies higher than 40 MHz , it serves the purpose of cancelling out the instrumental phase delay in the measurements.

Figure 4 shows the photothermal phase measurements of a 500 Å titanium, a 1000 Å titanium film, and a 2000 Å titanium-tungsten alloy film deposited on thick oxide. The differences between the phase measurements off the films and those off the reference sample are plotted against frequency. It will be seen that there is an approximate 18° difference in the measured phases at 15 MHz between the 500 Å and 1000 Å titanium films. The error of the phase measurement is about 1° . This means that an accuracy of 30 Å in a film thickness measurement should be obtained after calibration.

The phase response as a function of frequency of a 2000 Å thick titanium-tungsten alloy film has a slope and shape somewhat different from those of titanium films. This is a due to the different material properties of the films. Therefore, this technique could, in principle, be used to measure not only film thickness but also film composition.

Figure 5 shows the results of photothermal phase measurements of 150 Å and 5000 Å aluminum films, and 900 Å and 1400 Å tungsten films. Again, the phases plotted are the difference between the phases measured off the films and those measured off the reference sample. The error for tungsten films is about 0.25° . This corresponds to a thickness accuracy of 25 Å .

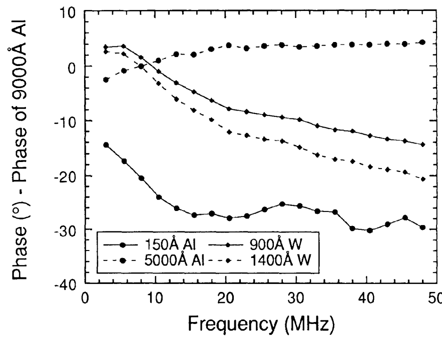

Fig. 5. Phase measurement of a photothermal signal of a 150 Å and a 5000 Å aluminum film and a 900 Å and a 1400 Å tungsten film on oxide. The vertical axis is the difference of the phase measured off a film and that of a reference sample (a 9000 Å aluminum film on oxide).

The phase error in the measurements of aluminum films is about 1°. The thicknesses of the two aluminum films are too far apart to estimate a possible accuracy for a thickness measurement. For the frequency range in the plot, because the diffusion length of thermal waves in aluminum is comparable to or larger than the heating beam spot size, heat diffusion is in both the vertical and radial directions. The linear correlation of the phase delay of a photothermal signal with film thickness no longer holds. Notice that the 5000 Å film gives less phase delay than the 150 Å film. This is because, for the 5000 Å film, the diffusion of heat radially plays a noticeable role in the phase of the surface temperature modulation. For very thick aluminum films, one needs to use a larger heating spot size to reduce the radial heat diffusion and maximize the dynamic range in phase measurement.

For very thin films, the effect of subsurface absorption becomes important. There are discrepancies between our three-dimensional theory and the experimental results. One of the reasons that we have assumed only top surface heating is to simplify the calculation. The metals we measured have absorption lengths ranging from 150-500 Å for infrared light. The effect of subsurface heating becomes noticeable when the absorption length is comparable to the film thickness. The bumps in the phase response of 150 Å aluminum film are real and repeatable. We believe that it is the result of optical interference in the aluminum film itself, for which the absorption length is of the order of 150 Å, because similar bumps do not exist for thicker films.

Accurate modeling of the phase response of a metal film can be very complicated. In addition to the factors mentioned above, one also needs to know the exact material properties of the film to predict its photothermal phase response. It is difficult because the properties of a deposited film are often very different from those of metal in bulk form, depending on the metallization method and process. The process dependent thermal resistance at the metal-oxide interface is a further complication to the modeling. However, our preliminary measurement results on various films have proven that, with an empirical calibration, photothermal phase microscopy can be a potential technique to measure a metal film thickness in VLSI devices or monitor a metallization process nondestructively.

The film thickness measurement has good transverse definition. Since the thermal wave is a highly damped diffusive wave, the measurement is only sensitive to structures within one diffusion length. At high frequencies (20 MHz and up), the diffusion length of a thermal wave in a metal is typically less than a few thousand Ångstroms. Therefore, the thermal wave is well confined under the laser spot. With a 1.0 micron beam spot, transverse resolution of this technique is minimum compared to other methods. A measurement can be carried out on a $3 \times 3\ \mu m^2$ pad.

CONCLUSIONS

We have developed a new, high-frequency photothermal phase microscope which uses

intensity-modulated laser beams to excite and probe thermal waves up to 500 MHz in a metal film. The reflection of the thermal waves from the bottom of a metal film changes the amplitude and phase of the surface temperature variation with respect to the heating beam modulation. The phase of the photothermal signal is used to measure the opaque film thickness.

Measurements have been carried out on various films with different film thicknesses. The results have shown that, with an empirical calibration, the technique is adequate to measure metal films such as aluminum, tungsten, titanium and their alloys in the range of a few hundred to a few thousand Ångstroms with an accuracy of about 30 Å . The discrepancy between the measurement and theory probably is the result of subsurface heating, uncertainty of the material properties, and optical interference. The technique needs no physical contact with the sample, and has good transverse resolution. It can be a potential technique for measuring metal film thicknesses in VLSI devices or for monitoring a metallization process nondestructively.

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