Mirage-effect-based depth profiling of micromachined silicon structures

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Abstract

A non-contact, non-destructive technique for the depth profiling of micromachined structures is presented. Based on the mirage or optical-beam deflection method of photothermal spectroscopy, an experimental measurement of a 5 μm step in silicon is given by way of illustration.

Keywords: Depth profiling; Micromachining; Mirage effect; Silicon

1. Introduction

Photothermal optical-beam deflection [1] (the mirage effect [2]) studies have been finding a wide range of applications for characterization of metals, semiconductors [3,4] and insulators [5]. With the widespread interest in silicon-based sensors and actuators, micromachining has become an active area of current industrial interest. We have applied the principle of mirage-based photothermal studies to non-contact depth profiling in micromachined silicon structures. The principle is based on the generation and utilization of thermal waves as a means of profiling and imaging sample surfaces. The experimental set-up and conditions reported are only illustrative in achieving depth resolutions of the order of a micron, and judicious optimization can further enhance the resolution.

2. Theory: thermal waves

A thermal wave [6] describes how a temperature modulation (T) propagates in a medium, and is obtained by solving the problem of unidimensional conduction of heat in a semi-infinite solid with periodic (ωn) surface temperature. The appropriate differential equation representing this problem of linear flow of heat (in the z-direction) is

$$\left( \frac{\partial^2 T}{\partial z^2} \right) + \frac{1}{D_n} \left( \frac{\partial T}{\partial t} \right) = 0 \quad (1)$$

where Dn is the thermal diffusivity of the material and is related to the thermal conductivity K, mass density ρ and specific heat c of the material by $D_n = K / (\rho c)$. The solution to Eq. (1) has the general form

$$T(\omega_n, t, z) = C \exp(-k_n z) \cos(\omega_n t - k_n z - \Phi) \quad (2)$$

and represents a temperature or thermal wave of wave number $k_n$ and wavelength $\lambda_n$ given by

$$\lambda_n = 2\pi / k_n = 2\pi (2D_n / \omega_n)^{1/2} \quad (3)$$

Within a depth $\lambda_n$, there is interaction between these waves and the thermal features of the substrate. Thermal wavelengths (at 100 kHz) for a few relevant materials are as follows: air = 50 μm, Si = 107 μm, silica = 11 μm, Au = 124 μm, CCl4 = 3 μm.

3. Experimental set-up

The experimental set-up, typical of a ‘mirage’ cell, is shown in Fig. 1. An Ar+ laser ‘pump’ beam, intensity modulated by means of an acousto-optic modulator (AOM), is incident parallel to the z-axis onto the sample under test. The sample is placed in the xy plane. A He–Ne laser ‘probe’ beam grazes over the sample surface, which is parallel to the z-axis, intersects the modulated Ar+ beam and is finally incident on a four-quadrant photodiode. The periodic variation in temperature at the surface of the silicon due to heating by the modulated Ar+ laser beam causes a corresponding temperature modulation in the gas adjacent to the sample surface. This periodic change in temperature in the gas in turn mod-
ulates the local refractive index of the gas with the same frequency as that of the modulated Ar$^+$ laser beam. Consequently the He–Ne laser probe beam oscillates as it passes through the heated region in the gas. This vibration can be sensed by a quadrant photodiode and a lock-in amplifier using a synchronous detection scheme. The sensitivity of this setup [7] is of the order of $10^{-11}$ rad Hz$^{-1/2}$ for an angular deviation corresponding to $10^{-5}$ °C Hz$^{-1/2}$ for the sample surface temperature variation in air, or $10^{-7}$ °C Hz$^{-1/2}$ for a surrounding transparent liquid medium such as CCl$_4$.

The sample, as shown in Fig. 1, is a p-type silicon wafer, 5–10 Ω cm resistivity, ⟨100⟩ ± 2° orientation and 300 μm thick. A step of 8 μm (as measured by an Alpha-Step instrument [8]) is made on the sample surface by means of reactive ion etching in Si$_4$/CHF$_3$ plasma. The sample can be scanned in the x-direction by means of a translation stage. The Ar$^+$ laser power incident on the sample is around 10 mW, focused to a spot of about 20 μm, and the He–Ne probe beam has a 100 μm waist in the interaction region.

In the experiments conducted, the focused laser pump beam (~20 μm spot size) is much smaller than the radial dimensions of the sample. Also the thermal diffusion length of the Si sample (~39 μm at 6 kHz modulation frequency) is much less than the sample dimensions. Over the interaction region between the pump and the probe beams (inset of Fig. 1), the pump beam (20 μm spot) is focused to a smaller spot than that of the probe beam (100 μm), and the probe beam waist also does not change over the confocal distance of the pump beam. With these considerations, the 1-D approximations (Eqs. (1) and (2)) to an essentially 3-D problem (heat flow in x-, y- and z-directions) in the present experimental situation can be shown to be valid [9]. This is illustrated in Fig. 2 by plotting the thermal wave phase as a function of the probe-to-sample distance, from which it is apparent that for probe-to-sample distances greater than about 50 μm (as in the present setup), the linear approximation is valid. Numerical simulations confirm this excellent match (Fig. 2).

4. Results and discussion

The experiment was carried out for various modulation frequencies, 4, 6, 8 and 10 kHz. A plot of the measured photothermal optical-beam deflection (mirage) phase, as a function of the scanned (x-) distance, is shown in Fig. 3. The phase readings were divided into two groups: those before (and including) 2.5 mm scanned distance and those after and including 3 mm distance, the reason for this grouping being that in between 2.5 mm and 3 mm scanned distance, at 2.9 mm, the step was found to be visually present (the pump
beam has irregular diffuse reflection). It may thus be seen that the surface dimension resolution in the location of the step is determined by the pump beam spot size. For better resolution, specially with reference to the practical applicability to micromachined structures, it will have to be focused to a few microns and the set-up automated [10,11], providing repeatable step sizes of the order of 0.1 μm. No readings were intentionally taken too near the step to avoid the effect of inhomogeneous thermal wave propagation.

All readings before the step were then fitted with a least-square quadratic straight line, and similarly for the post-step readings also. The respective straight lines were extended till the 2.9 mm scanned distance point, corresponding to the step in silicon, and the difference in phase noted (Fig. 3). Also observe the increase in value of the phase change with increasing modulation frequency (as the thermal diffusion length becomes smaller).

The results can be explained through thermal wave propagation. The present mirage set-up probes the thermal waves generated in air by heating of the sample surface. Due to the topology of the step, the He–Ne probe beam, though parallel, is at different heights from the sample surface, before and after the step (inset of Fig. 1). In other words, the probe beam intersects the generated thermal wave in air at different heights, hence the observed difference in measured phase. At a given frequency f₀ (ω₀/2π) of modulated heating, the thermal wave generated has a wavelength λ₀ given by Eq. (3), and undergoes a phase change of 360° within this distance. Quantitatively, the phase change ΔΦ, occurring due to the step of height h, is given quite simply by

\[ h = \lambda_0 (\Delta \Phi / 360°) \]  

At a modulated heating frequency of 4 kHz, the thermal wavelength in air is 256 μm. A phase change of 12° in the vicinity of the step position (Fig. 3) therefore indicates a step height of 8.3 μm. Similarly, at 6, 8 and 10 kHz, the measured phase change relates to a step height of 7.9, 8.2 and 8.2 μm, respectively.

These results compare very favourably with the 8 μm step measured by the Alpha-Step. A major advantage of the presented technique is its non-contact nature, allowing measurements at a distance, a condition which may not only be desirable but essential in certain applications. The technique has also been verified by measurements of steps of 28 and 36 μm. It is relevant to mention that similar logic has recently been applied for the determination of the depth of proton-exchanged layers in LiNbO₃ [10,11].

5. Error analysis

The error attendant on the basic scheme of measurement is essentially determined by Eq. (4). The accuracy of the step height (h) is dependent on the accuracy of the values of the phase difference (ΔΦ) and the thermal wavelength (λ₀). Using Eqs. (3) and (4), the worst-case relative error in the measurement of h can then be written as

\[ \Delta h/h = [\Delta \lambda_0/\lambda_0] + [\Delta (\Delta \Phi)/\Delta \Phi] \]

\[ = [\Delta D_0/D_0] + [\Delta \omega_0/\omega_0] \]

\[ + [\Delta (\Delta \Phi)/\Delta \Phi] \]

\[ = |\Delta K/K| + |\Delta \rho/\rho| + |\Delta c/c| \]

\[ + [\Delta \omega_0/\omega_0] + [\Delta (\Delta \Phi)/\Delta \Phi] \]  

(5)

The first three terms on the right-hand side of Eq. (5) involve material constants: thermal conductivity (K), mass density (ρ) and specific heat (c). Si, being a widely used and important material, has been the object of much investigation and therefore the values of its K, ρ and c can be said to be known accurately. The fourth term in the relative error depends on the accuracy of the frequency of periodic heating.
This periodic heating provided through the amplitude modulation of the Ar⁺ laser beam is at a frequency set through the signal source (Fig. 1). Signal generators and synthesizers commonly provide resolutions in the MHz–Hz range with accuracies of parts per million (ppm).

The last term involving relative error of the measured phase difference is the most significant. The phase of the thermal signal (at frequency fₚ) is measured by the lock-in amplifier connected to the output of a photodiode on which the incident He–Ne laser probe beam oscillates at a frequency corresponding to that of the periodic heating (fₚ). The measured lock-in amplifier signal tends to be corrupted with noise from various sources. Background noise originating from the laser, the electronics and the environment all contribute to the uncertainty in the measured phase. Laser intensities fluctuate, causing changes in the readings about the mean. The ambience contributes noise through convection and turbulence (air currents result in variation of index of refraction) or mechanical vibrations. For a quadrant photodiode with a typical noise floor level of, say, 0.5 μV, and 20 mV μm⁻¹ position sensitivity, the minimum detectable displacement will correspond to 25 × 10⁻¹² m, or equivalently, for the mirage system having the photodiode at a distance of 5 cm from the pump beam, to an angle of detection equal to 4 × 10⁻¹⁰ radians. This, in turn, is related to a periodic temperature change of the order of 10⁻³ °C and associated periodic refractive-index variation of air through which the probe beam passes [7,9]. Other sources of noise are unwanted light scattering on the position sensor, spurious signals due to dust particles on the sample, etc. Due precautions need to be taken to minimize/avoid all of the above.

6. Conclusions

A new non-contact technique for measuring step heights, using optical-beam deflection by thermal waves, has been presented. Depth measurements down to 8 μm have been shown by way of illustration. As discussed, enhanced resolutions of the order of a micron and better should be readily achievable by judicious optimization of various parameters, e.g., focusing of the pump beam and providing a small step size for translatory movement of sample will enhance the resolution in location of the step: increasing the frequency of modulated heating would decrease the thermal wavelength so that smaller step sizes (depths/heights) will have appreciable phase change; using media other than air, i.e., CCL₄, with low thermal diffusivity, for thermal wave generation; reduction of various contributions to noise, etc.

While the mirage effect already has wide applicability in characterization of metals, semiconductors [3,4] and insulators [5], the technique presented here would also enable non-contact depth profiling in micromachined structures, e.g., contouring of a silicon micromachined pressure sensor.

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References

[8] Alpha-Step 100, TENCOR Instruments, CA, USA.

Biographies

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Benoît C. Forget was born in St. Jerome, Quebec, Canada, in 1966. He received his engineering degree from the Ecole Polytechnique in Montreal and his Ph.D. from the Université Pierre et Marie Curie, where he is now maître de conferences. His main interest is in the application of photothermal methods to the study of thermal and electronic transport in semiconductors.

Daniele Fournier was born in Mauriac, Auvergne, France in 1945. She obtained her engineering degree from the Ecole Supérieure de Physique et de Chimie Industrielles de la ville de Paris in 1969, and her Ph.D. in 1979. She is a professor at the Université Pierre et Marie Curie. She is the co-author of the patent on the mirage detection apparatus and has been involved in photothermal science since 1979.