MODULATED INTERFERENCE EFFECTS AND THERMAL WAVE MONITORING OF HIGH-DOSE ION IMPLANTATION IN SEMICONDUCTORS

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Under sufficiently high dose and energy, ions implanted into a semiconductor will produce an amorphous layer throughout the range in which nuclear stopping is the dominant mechanism for slowing the ions. In arsenic implanted silicon, for example, this corresponds to doses greater than 10^{14} ions/cm^2 and energies above 10 keV. Using a model for thermal and plasma wave-induced modulated reflectance effects in semiconductors, we show that an optical probe beam will exhibit modulated interference effects which are directly related to the thickness of the amorphous layer and therefore, to the level of ion implantation. We also show experimental data which support the model and demonstrate the use of this thermal wave technique as a method for monitoring the ion implantation process in the high dose limit.

As a model for an ion-implanted semiconductor material in the high dose limit we consider a single amorphous layer of thickness d on an undamaged crystalline substrate as illustrated in Fig. 1.

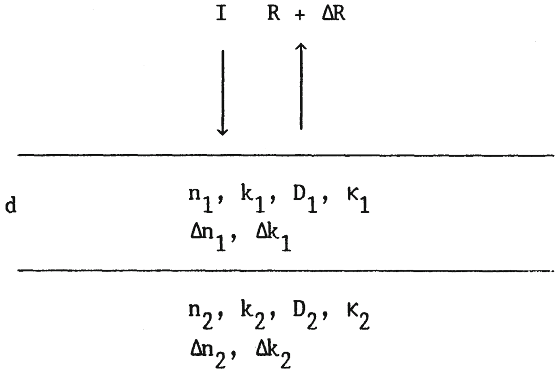

Fig. 1 Single amorphous layer model of ion implantation damage.

Shown in Fig. 1 are the refractive index, n_j, extinction coefficient, k_j, ambipolar diffusion coefficient, D_j, and thermal conductivity, κ_j, for the amorphous layer, j=1, and undamaged crystalline substrate, j=2. Also indicated on the figure is the effect of thermal and plasma wave-induced modulations in the optical constants, Δn_j and Δk_j, on the reflectance, R, of a probe beam with incident intensity, I. Simply stated, thermal and plasma wave-induced modulations in the optical constants result in a modulation, ΔR, of the reflected beam, an effect which is readily observed [1] and especially significant in semiconductors [2].

To begin the analysis, we recall the 1-dimensional thermal wave response for a single layer on a half-space as derived, for example, in [3]. Assuming that the absorption of the pump beam energy occurs at the surface, we have for the surface temperature T(0),

$$T(0) = \frac{iQ}{q_1\kappa_1}\left[\frac{q_1\kappa_1 - iq_2\kappa_2 \tan q_1d}{q_2\kappa_2 - iq_1\kappa_1 \tan q_1d}\right] \qquad (1)$$

where Q is the portion of absorbed pump beam intensity converted to heat on a time scale short compared to the modulation time, $1/\omega$. At MHz frequencies and with recombination times exceeding 10^{-7}s, Q is proportional to the above band gap energy. That is, recombination effects will not affect the qualitative aspects of this analysis. In silicon then, with an indirect gap of 1.1 eV and using an Ar^+ion laser at 488 nm as a pump, about 1.4 eV/photon contributes to the thermal wave with the remaining 1.1 eV carried away from the source region by the photogenerated electron-hole plasma. Also, in Eq.(1), $q_{1,2}$ are the thermal wave vectors in the layer and substrate defined in each case by,

$$q = (1 + i)(\omega\rho C/2\kappa)^{1/2} \qquad (2)$$

where ρ is the density and C is the specific heat.

As discussed in [2], the plasma wave response is obtained in an analogous fashion leading to the expression for the surface plasma density, N(0),

$$N(0) = \frac{iP}{p_1D_1}\left[\frac{p_1D_1 - ip_2D_2 \tan p_1d}{p_2D_2 - ip_1D_1 \tan p_1d}\right] \qquad (3)$$

where P is the portion of the absorbed pump beam intensity carried away from the source region by the electron-hole plasma and $p_{1,2}$ are the plasma wave vectors in the layer and substrate defined in each case according to,

$$p = (1 + i)(\omega/2D)^{1/2} \qquad (4)$$

Using the above expressions and assuming values used previously for amorphous and crystalline silicon [2]: $\rho_{1,2} = 2.33$ g/cm^3, $C_{1,2} = 0.703$ J/g°C, $\kappa_1 = 0.03$ W/cm°C, $D_1 = 0.1$ cm^2/sec, $\kappa_2 = 1.42$ W/cm°C and $D_2 = 20$ cm^2/sec, we obtain the results shown by the solid curves in Fig. 2 . From either the thermal wave or plasma wave response, one expects a monotonic increase with increasing d until the thickness of the amorphous layer exceeds the appropriate diffusion length. For the thermal wave, the diffusion length at the 1 MHz frequency employed in all of these calculations is about 0.5 μm and, as expected, the normalized magnitude of the surface temperature begins to level off as d increases beyond that point reaching a peak value at about 1 μm. In the asymptotic limit of an infinitely thick layer, the surface temperature will be about 7 times the

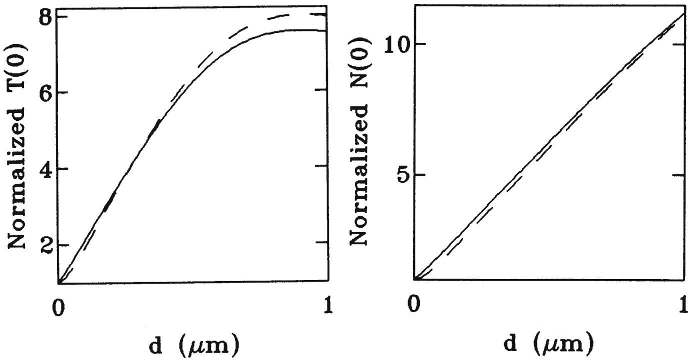

Fig. 2 Surface temperature and surface plasma density in 1-d model.

zero thickness value, ie, the sqare root of the ratio of the substrate to layer thermal conductivity.

Also shown by the dashed curves in Fig. 2 are the effects of including finite absorption of the pump beam in the layer and substrate. For the amorphous layer we assume an extinction coefficient of 1.3 and for the crystalline substrate an extinction coefficient of 0.08. In this 1-dimensional analysis and for the parameters used, we see that the optical absorption length is not a significant factor. However, in a 3-dimensional analysis this is not the case. Applying the analysis of [3] to the present problem, and assuming a 1 μm spot size for the pump beam, we obtain the results shown in Fig. 3.

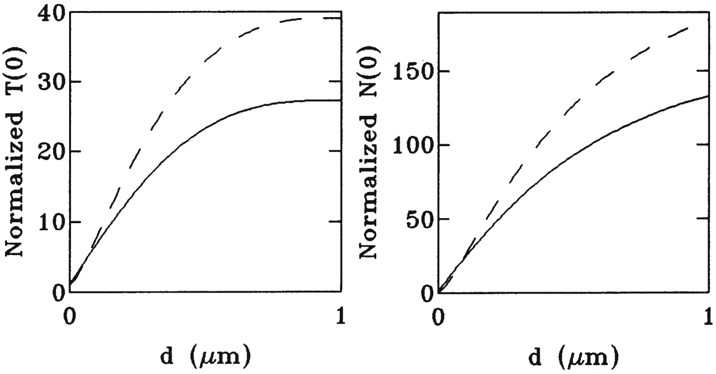

Fig. 3 Surface temperature and surface plasma density in 3-d model.

As discussed in [3], 3-dimensional heat flow leads to an increased dependence on thermal conductivity and, in the limit of zero modulation frequency or, equivalently, an infinitessimal spot size, the dependence approaches $1/\kappa$. Similarly, for the plasma wave, in this low frequency limit, we expect the dependence to approach 1/D as shown by the results in Fig. 3. The effects of a finite absorption length are now seen to be significant as shown by the dashed curves and can no longer be neglected in any quantitative analysis.

At this point what we have are results indicating a strong dependence of the thermal and plasma wave responses on the amorphous layer thickness, that is, an indication of good thermal and plasma wave sensitivity to the ion implantation process. To apply this in practice, however, we need to first consider the detection method.

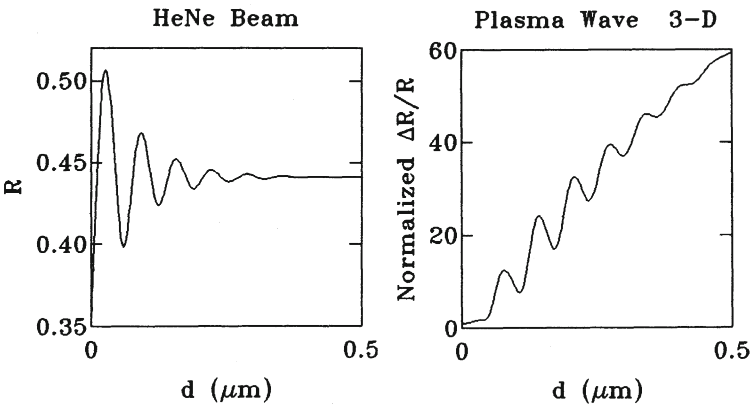

Fig. 4 Calculated reflectance and modulated reflectance curves.

As discussed earlier, the thermal and plasma wave-induced modulation of the optical reflectance is significant and easily measured in semiconductors. In many applications, the modulated reflectance, $\Delta R/R$, can be directly related to the modulation in the refractive index at the sample's surface, Δn, which depends directly on the modulated component of the surface temperature and plasma density [2]. For the present problem, however, the analysis is complicated by optical interference effects and the resulting $\Delta R/R$ is no longer a simple monotonic function of layer thickness. As an example we consider a HeNe probe beam at 633 nm with $n_1 = 4.7$, $k_1 = 0.7$, $n_2 = 3.9$ and $k_2 = 0.02$. Using the well known Fresnel equations [4], we obtain the reflectance curve shown in Fig. 4. Then assuming plasma wave-induced modulations in the refractive indices, Δn_1 and Δn_2, we obtain in a 3-dimensional calculation which includes the finite absorption length of the pump beam, the normalized modulated reflectance curve shown in Fig. 4.

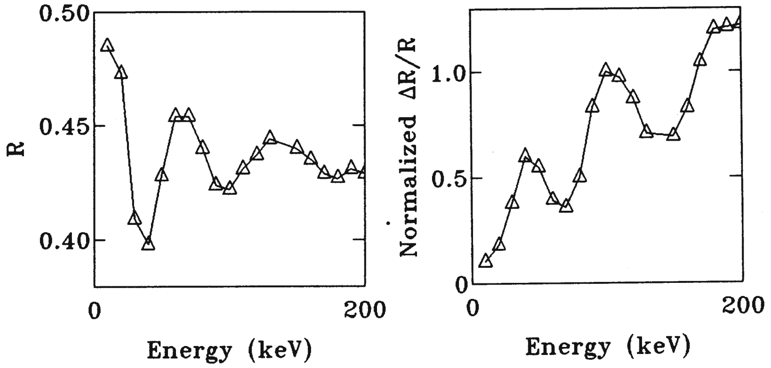

Fig. 5 Experimental reflectance and modulated reflectance curves.

For comparison, we have measurements on silicon samples that have been implanted with 10^{15} ions/cm^2 at energies ranging from 10 keV to 200 keV. Effectively, this implantation produces amorphous silicon layers ranging in thickness from about 100 Å up to about 2000 Å. The experimental results shown in Fig. 5 indicate that the simple model employed for the results in Fig. 4 is essentially correct.

In this work we have shown that a single amorphous layer model for high-dose ion implantation accounts for the modulated reflectance observed experimentally on silicon samples implanted with amorphizing arsenic ions. Finally, we note that in recent independent work by Wurm, et al [5], results similar to those presented here have been obtained.

ACKNOWLEDGEMENT

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