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Amorphization of ion-implanted layers in silicon using photoacoustic detection

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The influence of ion implantation in the thermal properties of silicon wafers at room temperature is investigated using the photoacoustic technique. It is suggested that the observed decrease of the values of both thermal diffusivity and conductivity, as the implantation dose increases, is due to the amorphization of the implanted layer.

In the last few years, the photoacoustic and related photothermal techniques^{1,2} have been successfully applied to the characterization of optical and thermal properties of semiconductors. In particular, in the case of ion-implanted semiconductors, the photothermal reflectance technique³⁻⁵ has been proven to be an important tool for monitoring the dose and uniformity of the implantation process. In this letter, we report on the dependence of the photoacoustically measured thermal diffusivity on the implanted dose of Zn^+ ions in silicon wafers. The importance of the thermal diffusivity as a physical parameter to be monitored is that knowledge is essential in designing optoelectronic devices, since power dissipation is an important mechanism in limiting the device performance.

The samples used were 388- μm -thick (100) oriented, p -type Si wafers cut in the shape of squares having $14 \times 14 \text{ mm}^2$ of area. The experimental batch consisted of four wafers implanted through the natural oxide layer at room temperature, with Zn^+ ions with doses between 10^{13} and $10^{16} \text{ ions/cm}^2$, at an energy of 150 KeV. The thermal diffusivity was measured using the phase-lag method described in Ref. 6. This method consists of measuring the relative phase lag $\Delta\phi = \phi_f - \phi_r$ at a single modulation frequency, between the rear surface illumination as depicted in Fig. 1. Using the thermal diffusion model of Rosencwaig and Gersho,⁷ the phase lag $\Delta\phi$ is given by

$$\tan(\Delta\phi) = \tanh(la_s) \tan(la_s), \quad (1)$$

where l is the sample thickness, and $a_s = (\pi f/\alpha)^{1/2}$ is the thermal diffusion coefficient of a sample with thermal diffusivity α at a modulation frequency f . The light source used was a 180 mW Ar-ion laser, which after being mechanically chopped, is divided by a beamsplitter and the resulting beams are directed to opposite sides of the photoacoustic cell (c.f., Fig. 1). The output signal amplitude and phase from the microphone were recorded using a lock-in amplifier.

The thermal conductivity, k , was measured using the temperature rise method under continuous white light il-

lumination. The samples had both surfaces sprayed with black paint. In this way, we ensured not only a good light-absorbing surface but also the same heat transfer coefficient for each surface. The samples were adiabatically suspended in a dewar which was subsequently vacuum sealed. Under these conditions the main heat-loss mechanism is the loss by radiation. The Dewar had an entrance glass window through which the continuous white light beam was focused onto one of the sample surface. On the opposite surface we had attached a thermocouple to the sample using thermal paste, in this way the temperature evolution of the back surface could be monitored as a function of time. It can be shown that the long-term time evolution (i.e., for times greater than the heat diffusion time $\approx l^2/\alpha$) of the back surface temperature rise is given by

$$\Delta T = \alpha \tau I_0 / l k [1 - e^{-t/\tau}], \quad (2)$$

where I_0 is the intensity of the incident light beam, and $\tau = l k / 2 \alpha H$ is the rising time. Here, $H = 4 \sigma T_0^3$, where σ is the Stefan-Boltzmann constant, and T_0 is the ambient temperature, H is the radiation heat transfer coefficient. The thermal conductivity was obtained using the best-fit values of τ and the previously obtained values of α .

FIG. 1. Schematic arrangement for the two-beam photoacoustic measurement of thermal diffusivity.

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FIG. 2. Thermal diffusivity as a function of dose for Zn^+ -implanted silicon samples.

Figures 2 and 3 show the results for the thermal diffusivity and thermal conductivity, respectively, as a function of the Zn^+ dose, over the range of 10^{13} – 10^{16} ions/cm². At low doses, the measured values of the thermal diffusivity and conductivity were $0.87 \text{ cm}^2/\text{s}$ and $1.47 \pm 0.03 \text{ W/cm K}$, respectively. These values are in good agreement with the ones typical of undamaged samples, as reported in the literature.² As the dose increases, both parameters decrease such that, at a dose of 10^{16} ions/cm², the thermal diffusivity exhibits a 16% decrease, whereas the thermal conductivity is reduced by 24%. We attribute this sensitivity of the thermal properties to doping levels to the higher degree of lattice damage caused by implantation. In fact, it has been known for some time^{8–11} that the ion-implanted layer undergoes a crystalline-to-amorphous transition as a function of the dose. For given implantation conditions of ion mass, energy, and temperature, the critical dose Φ_c is the experimental quantity which characterizes the implanted layer amorphization process. According to Christel *et al.*,¹¹ if the implanted ions displace 10% of the lattice ions, the sample can be considered amorphous. If fewer host atoms are displaced, one talks of an inhomogeneous layer composed of amorphous clusters within a crystalline matrix. Thus, the implanted layers' amorphization increases with the dose up to a critical dose, further implantation will not likely cause any additional structural change, but will slightly increase the

FIG. 3. Thermal conductivity as a function of dose for Zn^+ -implanted silicon samples.

FIG. 4. Critical amorphization dose Φ_c as a function of atomic number Z at room temperature.

thickness of the damaged layer. In Fig. 4 we present the variation of the critical dose for amorphization as a function of the atomic number, Z , of the ions implanted in Si at room temperature with an energy of 150 KeV. It follows from Fig. 4 that the critical dose for Zn^+ ion implantation is of the order of 3.5×10^{14} ions/cm². On the other hand, Figs. 2 and 3 tell us that above a dose of roughly 4×10^{14} ions/cm² there is a saturation tendency of both α and k with increasing dose. Comparing this value of implantation dose with the critical dose for Zn^+ we conclude that the observed behavior of α and k above the 4×10^{14} ions/cm² dose may be attributed to the crystalline-to-amorphous transition. Physically, one would expect that the main effect of the amorphization process is to reduce both thermal diffusivity and conductivity, as compared with those values of the pure crystalline phase. However, the observed degradation of the thermal properties, as a function of ion implantation reflects the average effect over two regions, the amorphous layer, and the crystalline substrate, and not the actual degradation in the implanted region only. To photoacoustically single out the implanted region (estimated to be roughly 1000 Å thick) we should monitor the photoacoustic signal at modulation frequencies greater than, roughly, 16 MHz. Finally, the fact that the slopes of the curves of α and k , as a function of the implantation, is nonvanishing at high doses may be reflecting the expected slight increase of the amorphous layer thickness once the amorphization process has been set in.

To conclude, we have shown in this letter the sensitivity of the thermal properties of silicon to implantation doses. These results are particularly important for the photothermal diagnostics techniques used in the semiconductor industry. To achieve higher device yields, in metal oxide semiconductor (MOS) and bipolar technologies, it is indispensable to characterize and control the various amorphization and recrystallization processes. The thermal diffusivity is the essential parameter when performing photothermal depth profile and uniformity studies.

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