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Noncontact Carrier Lifetime Depth Profiling of Ion-Implanted Si Using Photothermal Radiometry

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Introduction. Recently, a generalized methodology for carrier lifetime (τ) and carrier diffusivity (D_n) depth profile reconstructions was developed [1] which was the result of the realization that an electron–hole photoexcited plasma in semiconductors behaves like a carrier density diffusive wave, and, therefore, it can be theoretically treated as a plasma harmonic oscillator (PHO). In the present note the technique of frequency-scanned infrared photothermal radiometry (PTR) is applied to the foregoing PHO methodology, in order to obtain reconstructed carrier lifetime depth profiles of inhomogeneous ion-implanted semiconductors. The objective of this note was to study the depth distribution of any electronically-sensitive defects through the process of carrier transport property reconstruction after a thermal anneal, *via* the reconstruction of the corresponding photoexcited carrier lifetime depth profiles.

Experimental. The experimental setup for the laser PTR method used to measure the frequency dependencies of the surface plasma density magnitude and phase has been described elsewhere [2]. The investigated set of n-type Si samples included one implanted with P^+ ions (10^{13} cm^{-2}; 50 keV), and five implanted samples thermally annealed at various temperatures: 350 °C, 500 °C, 800 °C, 1000 °C and 1100 °C. A non-implanted and unannealed n-type Si sample was used as a reference ($\tau = 75$ μs, $D_\mathrm{n} = 20$ cm^2/s and $s = 800$ cm/s).

Fig. 1 shows the $M(\omega)$ ratios of the experimental PTR amplitudes obtained for the implanted and annealed Si samples, normalized to that from the reference non-implanted Si sample. As can be seen from Fig. 1, the process of ion-implantation introduces a significant change in the PTR-amplitude frequency responses with respect to those of the non-implanted sample. It is seen that the 350 °C to 1100 °C anneals only partially restored the damaged subsurface layers and reduced the number of electronically-sensitive defects in the material bulk to varying degrees, depending on the departure of the Log $(|M(\omega)|)$ from the zero-level line (reference) in Fig. 1. The most effective restoration of the electronic properties of an implanted sample appears to be the anneal at 800 °C. The effect of negative annealing was observed, as the PTR-amplitude frequency responses after the very-high temperature (1000 °C and 1100 °C) anneals are below the intermediate 800 °C anneal, closer to those obtained after the less effective low-temperature (350 °C to 500 °C) treatments.

Results and discussion. The inversion algorithm allowing for the reconstruction of $\tau(x)$ profiles was described in detail recently [1]. Briefly, a computer algorithm employing the two-dimensional Broyden's method redefines (upgrades) the pair of analytical profile parameters in the expression $\tau(x) = \tau_\mathrm{b}(1 - \Delta \exp(-qx))^2$; $\Delta = |(\tau_0/\tau_\mathrm{b})^{1/2} - 1|$, where τ_0 is the surface lifetime, q is the profile steepness, τ_b is the known bulk lifetime (reference wafer). A pair (τ_0, q) is sought, which satisfies the minimum conditions $|M_\mathrm{exper}(\omega_i)| - |M_\mathrm{theor}(\omega_i)| = 0$ and $|\Phi_\mathrm{exper}(\omega_i) - |\Phi_\mathrm{theor}(\omega_i) = 0$ simultaneously for each modulation frequency ω_i [1].

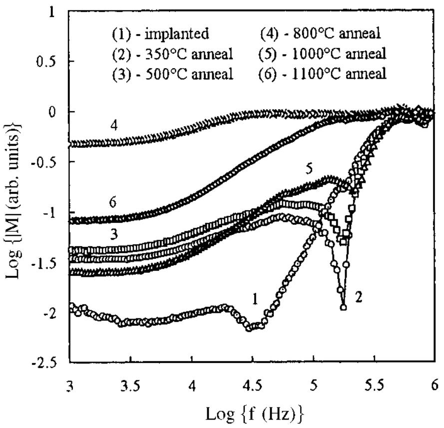

Fig. 1

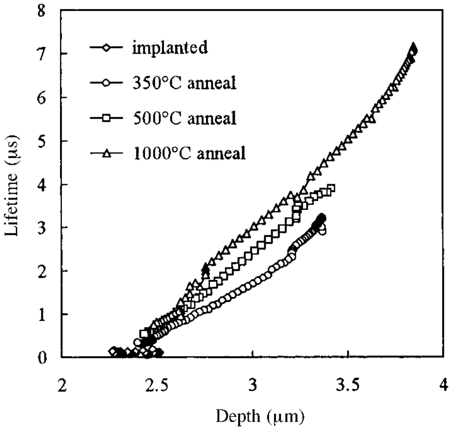

Fig. 2

Fig. 1. Experimental PTR-amplitude frequency responses

Fig. 2. Reconstructed $\tau(x)$ profiles

Fig. 2 shows the results of $\tau(x)$ depth profile reconstruction using the inversion algorithm. As expected, the ion-implanted unannealed sample with highly damaged sub-surface layers has a very short near-surface (within 2.5 µm) carrier lifetime of about 0.2 µs. Annealing treatments at 350 and 500 °C increased the near-surface τ values up to 3 to 4 µs, within 3 to 4 µm of depth (Fig. 2). The most effective lifetime restoration, however, appears to be produced after the thermal annealing at 800 °C which resulted in a nearly homogeneous carrier lifetime depth profile with much longer τ values (10 to 20 µs, not shown in Fig. 2). Nevertheless, further increase of the annealing temperature to 1000 °C has not improved the electronic property restoration: it produced roughly the same result as in the case of low temperature, 350 and 500 °C, anneals with τ increasing from 0.5 µs near-surface to 7 µs near-bulk after the anneal, Fig. 2, within 4 µm below the sample surface (negative annealing). Finally, the thermal treatment at the highest temperature of 1100 °C allows improvement of the electronic properties and brings the near-bulk carrier lifetime values close to 6 µs, a level only second to the 800 °C anneal.

References

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