Monitoring of ion implantation in Si with carrier plasma waves using infrared photothermal radiometry

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Photothermal infrared radiometry was used for monitoring the ion implantation in Si wafers implanted with phosphorus to doses in the range of $5\times10^{10}-1\times10^{16}$ ions/cm^2 at different implantation energies. Quantitative results on the sensitivity of the carrier plasma-dominated radiometric signal to the implantation dose and energy are presented and compared to those obtained using a commercial implantation monitoring instrument. © *1997 American Institute of Physics.* [S0003-6951(97)01037-1]

Ion implantation is a very important technological process in the modern microelectronics industry. It is widely recognized that integrated circuit performance and yield are strongly dependent on the accuracy and uniformity of the implanted ion dose. This is especially true for some critical implantation steps such as the low-dose implant adjustment of the threshold voltages of the integrated circuit.

Since the mid-1980s various photothermal techniques have been developed for the characterization of ion-implanted semiconductors.[1] The noncontact nondestructive character of the thermal wave-dominated techniques—photomodulated reflectance (PMR),[2–7] photoacoustic spectroscopy,[8] and photothermal beam deflection spectroscopy[9–11]—makes them very useful for monitoring of ion implantation. The PMR technique has already progressed from a laboratory measurement method to a commercially available ion implantation monitoring thermal wave (TW) system.[12,13]

Another recently established noncontact photothermal technique which has a number of potential advantages over existing methodologies in characterization of both the thermal and electronic properties of semiconductors, is infrared photothermal radiometry (PTR), which allows the measurements of the optically induced emission of blackbody radiation at the surface of a semiconductor.[14–17] It has been shown that the PTR signal is extremely sensitive to the carrier plasma-wave effects in semiconductors and possesses up to five orders of magnitude higher carrier plasma-to-thermal contrast than that of the PMR method.[18] This fact makes the application of the PTR technique for ion implantation monitoring with carrier plasma waves technology particularly attractive. Although the PTR measurements on ion-implanted Si wafers with qualitative analysis of the influence of thermal annealing have been reported earlier,[19] no quantitative experimental study has been done yet regarding the efficiency and sensitivity of the carrier plasma wave to implantation-induced damage in Si.

In this letter we present quantitative experimental results on the sensitivity of the PTR signal to the implantation dose and energy and compare it with the results obtained using a commercial TW instrument.[13] All photothermal measurements in this work have been performed using the PTR setup described earlier.[15,16] Experimental PTR-amplitude and phase-frequency scans were obtained from the near-center region of 36 Si wafers (B-doped, $\rho\sim14-24\ \Omega$ cm, thickness 510–520 μm) implanted with phosphorus to various doses from 5×10^{10} ions/cm^2 to 1×10^{16} ions/cm^2 (12 different doses) at each of the three implantation energies: 50, 100, and 150 keV. The phosphorus implantation was performed through a thin oxide layer at room temperature. A nonimplanted Si wafer from the same lot was used as a reference. TW surface scans of each implanted wafer and the reference were performed before the PTR measurements, and the TW results obtained from the near-center region of the wafer were selected for the comparative analysis.

Figure 1 represents the results of the PTR-amplitude and phase-frequency scans obtained from the nonimplanted reference wafer and from 12 Si wafers implanted at 50 keV. For the nonimplanted wafer the PTR signal exhibits carrier plasma wave dominated behavior[15–17] with the PTR amplitude saturated at low modulation frequencies [Fig. 1(a)] and the PTR phase tending to saturate at $-90°$ along the high frequency edge [Fig. 1(b)]. Simultaneous fitting of the experimental amplitude and phase data for the reference sample using the corresponding theoretical model[15,17,18] yielded the following values: minority carrier lifetime $\tau=10.5\ \mu$s, carrier diffusivity $D_n=30$ cm^2/s, surface recombination velocity $s=100$ cm/s, thermal diffusivity $D_{th}=0.8$ cm^2/s, and the relative weight of the carrier plasma and thermal components in the total PTR signal, expressed as a ratio of the plasma-to-thermal coefficients in the expression for the PTR signal,[17,18] $\eta=1.6\times10^3$ a.u.

For implanted wafers, η decreases gradually with increasing implantation dose from $\eta=9.5\times10^2$ a.u. (dose 5×10^{10} cm^{-2}) down to $\eta=6.6\times10^1$ a.u. for 1×10^{16} cm^{-2} implantation dose, resulting in a smooth transition between the plasma-dominated PTR-signal behavior at low doses and nearly pure thermal signal at high implantation doses [curve no. 12 in Fig. 1(a)]. Fitting of the foregoing experimental frequency scans resulted in practically the same values of the surface recombination velocity for all implanted wafers $s=7.3$ m/s, a drastic increase with respect to that for a refer-

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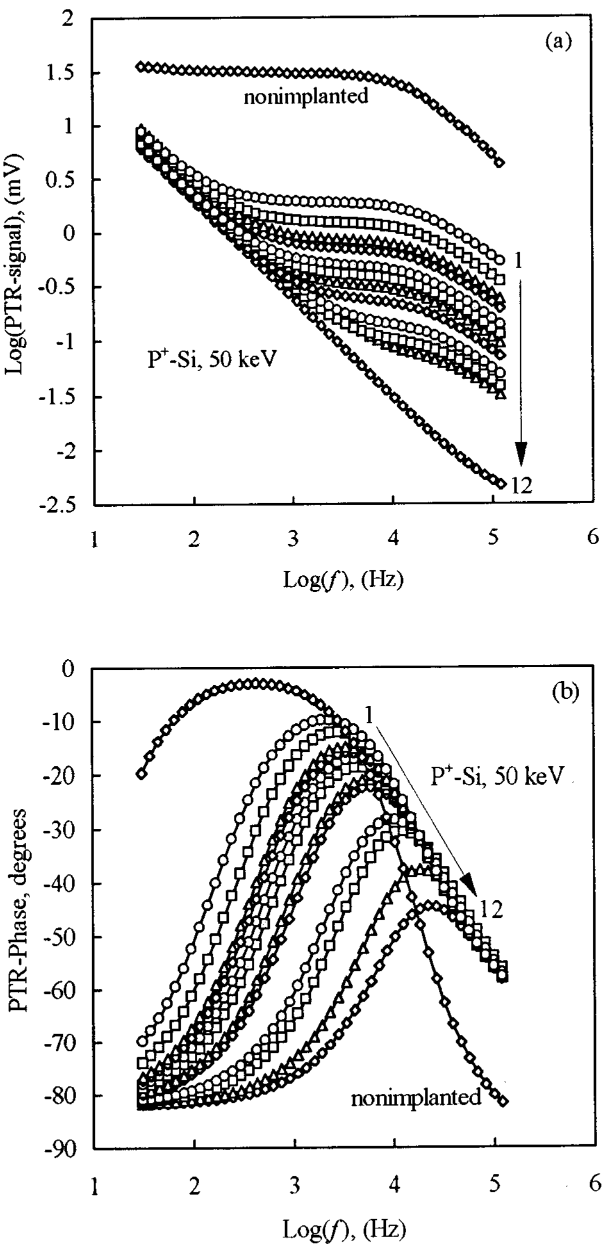

FIG. 1. Experimental PTR amplitude (a) and phase (b) frequency responses obtained from a nonimplanted reference wafer and Si wafers implanted with P^+ ions of 50 keV energy to various doses (ions/cm^2): (1) 5×10^{10}; (2) 1×10^{11}; (3) 5×10^{11}; (4) 1×10^{12}; (5) 5×10^{12}; (6) 1×10^{13}; (7) 5×10^{13}; (8) 1×10^{14}; (9) 5×10^{14}; (10) 1×10^{15}; (11) 5×10^{15}; (12) 1×10^{16}.

ence sample. No significant variations with dose have been observed for either D_n or D_{th}.

In the carrier plasma-dominated frequency region, the PTR signal has been found to be extremely sensitive to the damage introduced by ion implantation even at low doses and energies. At 10 kHz modulation frequency the difference between the PTR amplitudes from the nonimplanted wafer and the wafer implanted with the lowest dose/energy (5×10^{10} cm^{-2}, 50 keV) is more than one order of magnitude [Fig. 1(a)], thus allowing for the monitoring of ion implantation with dose and/or energy much lower than these values. The ratio of the corresponding TW signals from the same wafers is ~3.

The same quantitative analysis of the PTR-amplitude

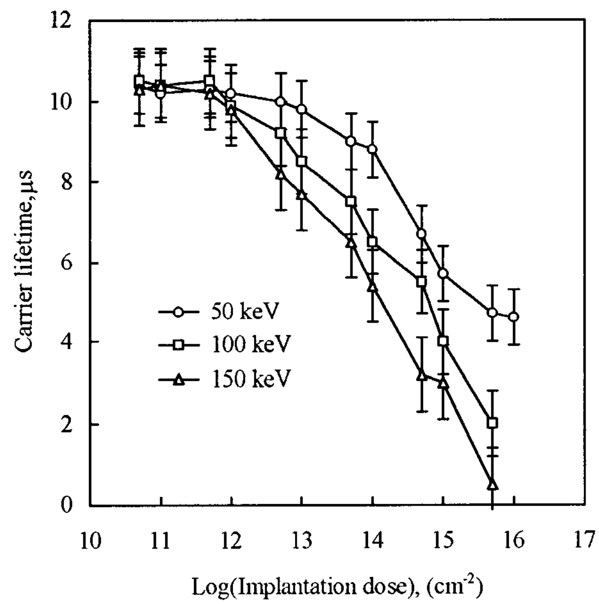

FIG. 2. Values of the minority carrier lifetime evaluated from the PTR amplitude and phase frequency responses as a function of implantation dose for implantation energies of 50, 100, and 150 keV.

and phase-frequency responses obtained for 100 and 150 keV implanted sets of Si wafers allowed the monitoring of the variations of the carrier lifetime with implantation dose and energy (Fig. 2). As the implantation dose/energy increases, τ remains unchanged and equal to that in a reference wafer (~10 μs) up to a threshold value of the dose ($\sim10^{12}$ cm^{-2}) and then starts to decrease with a rate which is implantation energy dependent (Fig. 2). This effect is related to the fact that the PTR technique is measuring the photoexcited carrier lifetimes in layers lying deeper than the thickness of the implanted layer (<1 μm). Thus, the value of τ in implanted Si wafers is unaffected by damage introduced by ion implantation to the uppermost layer until the

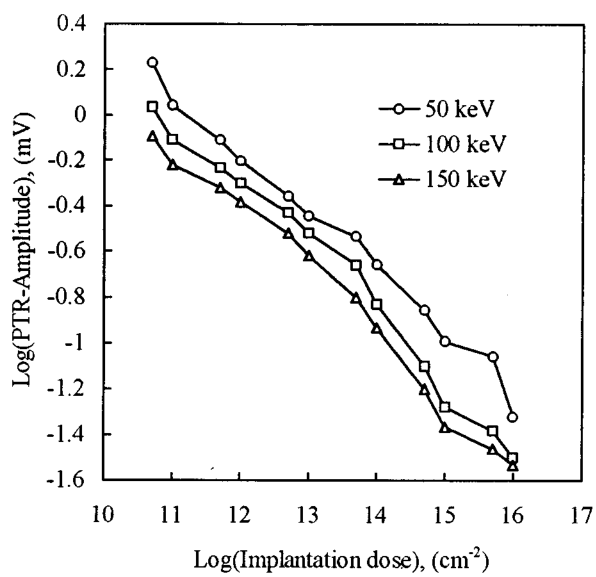

FIG. 3. Experimental dependencies of PTR amplitude on implantation dose for 50, 100, and 150 keV implantation energies taken at 10 kHz modulation frequency.

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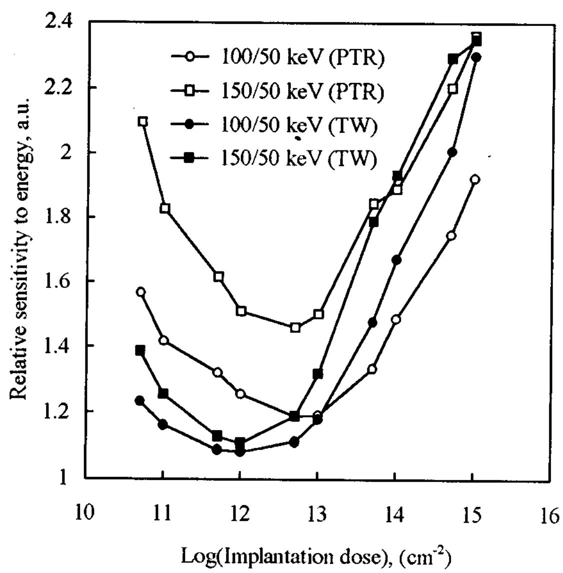

FIG. 4. Implantation dose dependencies of relative sensitivities to energy of the PTR amplitude at 10 kHz and TW signal. Relative sensitivity to implantation energy is defined as a ratio of the corresponding parameters obtained for a high-energy (100 keV, 150 keV) samples to that measured for 50 keV implanted wafer.

effective depth of the electronically sensitive defects significantly exceeds the thickness of the implanted layer at high doses and/or energies.

Figure 3 presents the PTR amplitude in the plasma-dominated region (10 kHz) as a function of the implantation dose for various implantation energies. The lattice damage induced by the ion beam causes the plasma wave signal to decrease below that of the nonimplanted reference wafer in a pronounced manner. The functional dependencies exhibited by the data in Fig. 3 are smooth, monotonically decreasing and gradual, such that a very good sensitivity of the PTR amplitude to the implantation dose is maintained over more than five orders of the implantation dose.

The relative sensitivity of the carrier plasma waves to the implantation energy defined as the ratio of the PTR amplitude obtained from a high energy (100 keV, 150 keV) implanted wafer to that for the 50 keV implanted wafer at 10 kHz is compared in Fig. 4 with the corresponding TW results. It can be seen that both photothermal methods exhibit similar U-shape dose behavior with a minimum of sensitivities occurring in the implantation dose range of $(1-10)\times 10^{12}$ cm^{-2} (Fig. 4). In this region the decrease in sensitivity of both methods is probably associated with the effects introduced by the earlier stages of amorphization process in the implanted layer. However, in this region of doses the PTR sensitivity to energy is slightly higher than that of the TW signal: 1.5 for 150/50 keV ratio and 1.2 for 100/50 keV ratio compared to TWs values of 1.15 and 1.1, respectively. At low implantation doses the carrier plasma wave (PTR method) sensitivity to energy increases significantly with respect to its value in the minimum, being approximately the same as that for the thermally dominated TW signal at the high dose end.

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