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Common-mode-rejection demodulation lock-in technique for high-resolution characterization of ion implantation in silicon wafers

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In this article, we present the use of frequency-scan and lock-in common-mode-rejection demodulation (CMRD) laser photothermal radiometry to the study of B^+, P^+, and As^+, ion implanted silicon wafers, with and without surface-grown oxides. The implantation energy of the wafers was 100 keV in all the wafers and doses ranged between 1×10^{11}–1×10^{13} ions/cm^2. The CMRD technique is a new demodulation method that was tested after a theoretical study and its implementation in hardened Zr–2.5Nb samples. This technique is applied to silicon ion-implantation monitoring and we report a superior signal resolution in dose range where the conventional frequency scans essentially overlapped: B^+ implants in the dose range 1×10^{12}–1×10^{13} ions/cm^2, and P^+ implants in the 1×10^{11}–10^{13} ions/cm^2 range. In all other cases where conventional frequency scans could resolve implantation doses, CMRD did not present any significant resolution advantages. It was further established that the pulse separation increment $\delta\Delta$ is the critical CMRD wave form parameter, which controls dose resolution through substantial signal background and noise suppression. The dose resolution improvements afforded by the CMRD technique may be important toward better control of the ion-implantation process in electronic devices, in a dose range which has traditionally been difficult to monitor optically owing to the effects introduced by the early stages of the amorphization process in the implanted layer. *© 2003 American Institute of Physics.* [DOI: 10.1063/1.1517739]

I. INTRODUCTION

Conventional frequency domain photothermal methods use sinusoidal-wave or 50% duty-cycle square-wave laser intensity modulation, followed by lock-in amplifier (LIA) demodulation. In this work, we present an application of the new lock-in common-mode-rejection demodulation (CMRD) technique[1,2] to Si wafer diagnostics. The particular repetitive wave form is shown in Fig. 1. In principle, it is possible with this new technique to obtain a complete suppression of baseline signals because it takes advantage of the details of the two-phase lock-in demodulation process.[3] If the sample is irradiated with a periodic optical wave form consisting of two square pulses (Fig. 1), the LIA output is given by the difference of the physical response wave forms produced by each of the two pulses. The main advantage of CMRD is the suppression of LIA baselines, which in turn, enhances the dynamic range of the measurements. The CMRD technique has shown[2] considerable measurement resolution improvement in cases where minute changes in sample thermophysical properties produce signal differences too small to be resolved by conventional square-wave modulation. This resolution problem also appears with the ability of conventional laser photothermal methodologies to monitor ion-implantation doses in Si wafers: In some ion-implantation dose ranges (functions of ion-implantation species), conventional methods such as laser thermoreflectance and photothermal radiometry have shown[4] relatively low dose resolution. In this article, we report a comparative dose resolution study of conventional frequency-domain and CMRD photothermal radiometry (PTR) using a set of Si samples implanted with 100 keV B^+, P^+, and As^+ in the conventionally low-resolution dose range of 1×10^{11}–1×10^{13} ions/cm^2.

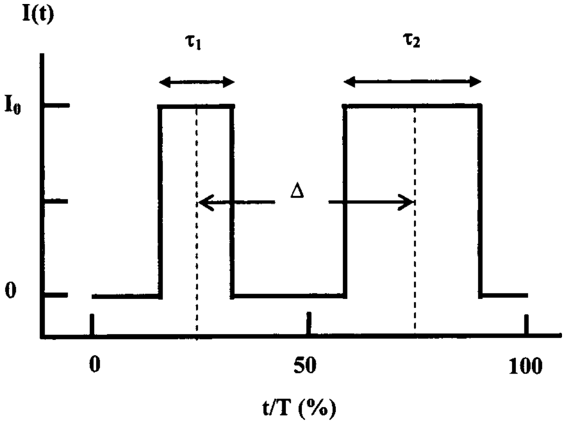

FIG. 1. CMRD optical excitation wave form. Horizontal time units are expressed as percentage of a full repetition period T, τ_1, and τ_2 are the corresponding square pulsewidths, and Δ is the center-to-center pulse separation.

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TABLE I. Si-wafer-ion-implantation matrix. Implantation energy 100 keV for all wafers.

Ion-implant species	Oxide	Dose
As	100 A	1×10^{11}
As	100 A	4×10^{11}
As	100 A	1×10^{12}
As	100 A	4×10^{12}
As	100 A	1×10^{13}
As	0 A	1×10^{11}
As	0 A	4×10^{11}
As	0 A	1×10^{12}
As	0 A	4×10^{12}
As	0 A	1×10^{13}
P	0 A	1×10^{11}
P	0 A	4×10^{11}
P	0 A	1×10^{12}
P	0 A	4×10^{12}
P	0 A	1×10^{13}
B	0 A	1×10^{11}
B	0 A	4×10^{11}
B	0 A	1×10^{12}
B	0 A	4×10^{12}
B	0 A	1×10^{13}

II. EXPERIMENTAL RESULTS AND DISCUSSION

A batch of twenty 4 in. Si wafers were used in this work. Three sets of five wafers were ion implanted with B^+, P^+, and As^+ and another set with a grown thermal oxide (100 Å thick) was also implanted with As^+, Table I. Frequency scans were performed in the range of 10 Hz–100 kHz using the standard PTR experimental setup.[5] Then, CMRD scans at a fixed frequency (4 kHz) were performed by replacing the square-wave form generator with a programmable wave form synthesizer (Stanford Research Systems Model DG535) and appropriate software. An Ar-ion laser beam (515 nm) was focused on a spotsize of ~50 μm at an average power of 50 mW. Every wafer was probed near the center point. Wave form center-to-center scans (separation Δ in Fig. 1) were performed with $\tau_1 = 5$ ms and $\tau_2 = 25$ ms. Figure 2 shows the four CMRD lock-in signal outputs, amplitude (mag), phase, in-phase (IP), and quadrature (Q), for the group of P^+-implanted wafers using $\delta\Delta = 5\%$ pulse separation increments. In the computational program, from the IP and Q lock-in amplifier signals, the amplitude and phase were calculated $\{\text{mag}=(\text{IP}^2+Q^2)^{1/2},\ \text{phase}=\text{arctg}(Q/\text{IP})\}$. From Fig. 2 and similar plots with respect to the remaining

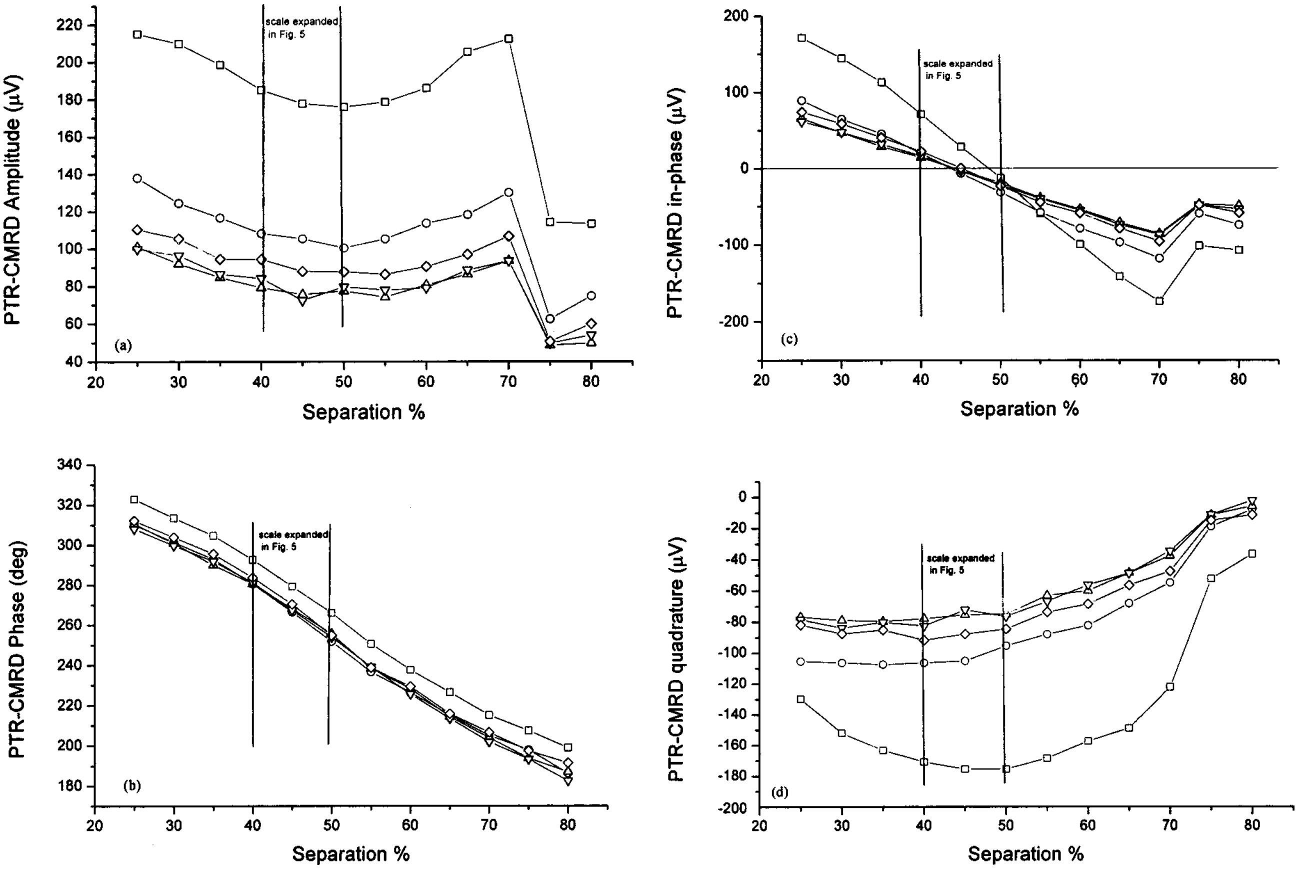

FIG. 2. (a) Amplitude; (b) phase; (c) in-phase; and (d) quadrature of the PTR-CMRD signal output of P^+ ion-implanted Si wafers. Doses (ions/cm^2): (□) 1×10^{11}; (○) 4×10^{11}; (△) 1×10^{12}; (▽) 4×10^{12}; (◇) 1×10^{13}.

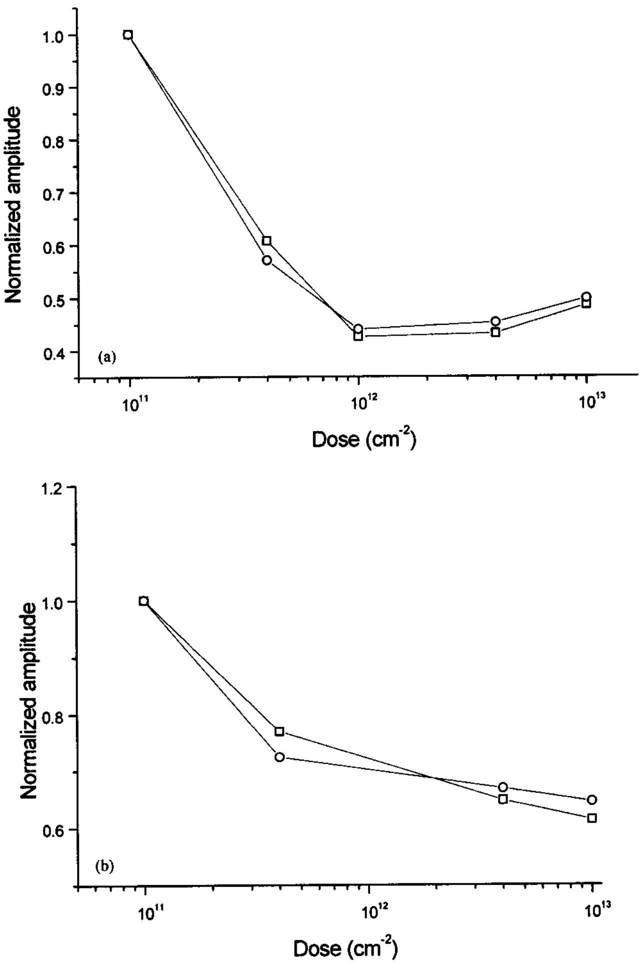

FIG. 3. 4 kHz frequency scans using a 50% duty-cycle square wave form and CMRD amplitude signals from (a) P^+-implanted and (b) As^+-implanted (without a surface oxide) Si wafers. For direct comparison, both sets of data points are normalized to the first datum. (□) Frequency scan; (○) CMRD scan.

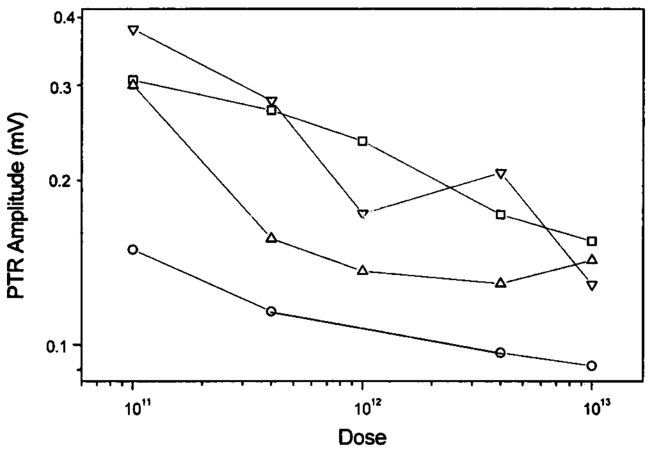

FIG. 4. PTR frequency-scan amplitude dependencies on implantation dose at 4 kHz. (▽): B^+; (△): P^+; (○): As^+ (unoxidized); and (□): As^+ (with 100 A thick oxide layer).

wafer groups, it was found that among the four possible CMRD signal channels, the amplitude and quadrature signals were optimal in terms of dose resolution. Figure 2 exhibits better resolution for the P^+-implanted signals than either frequency scan or time scan (not shown) primarily due to noise suppression, yet the overlap between the 1×10^{12} cm^{-2} and 4×10^{12} cm^{-2} remains essentially unresolved. This is verified in Fig. 3 which shows a comparison of signal amplitude changes with an implantation dose between the frequency scans and the CMRD scans for the P^+- and As^+-implanted wafers. It is observed that there is no advantage to using the CMRD for well-resolved-scanned PTR signals. This observation is reasonable, because, for large dose-generated PTR signal changes the baseline suppression ability of the CMRD is dominated (or overshadowed) by the natural signal differences among the corresponding PTR curves. In Fig. 4, with the exception of the anomalous nominal 4×10^{12} cm^{-2} B^+ and 1×10^{13} cm^{-2} P^+ ion implants, the decreasing order of PTR amplitudes with increasing dose and with increasing ionic mass (B^+, P^+, and As^+) for the unoxidized wafers is consistent with the increasing degree of damage incurred to the Si lattice by the progressively larger doses and ions. It is interesting to note the relatively large restoration of PTR amplitude exhibited by the As^+-implanted wafers, as expected from the decreasing defect density at the SiO_2-Si interface.[6,7] In Fig. 4, the signals for the various doses of As^+-implanted wafers are well separated. From the results of Figs. 2 and 3, it is apparent that the size of the increments $\delta\Delta$ may control the dose resolution of the technique in the near-saturation dose range. Therefore, the $\delta\Delta=5\%$ increment scans (Fig. 2) were followed by more highly resolved $\delta\Delta=1\%$ increment scans in the 40%–49% range. Results are shown in Fig. 5. The effective suppression of the instrumental signal baseline and noise level, germane features of the differential two-pulse wave form of Fig. 1, allows the use of a higher lock-in amplification range resulting in a considerably improved signal-to-noise ratio over that of Fig. 2. The narrower-range $\delta\Delta=1\%$ increment scan is capable of superior and complete resolution of the 1×10^{12} cm^{-2} and 4×10^{12} cm dose curves.

III. CONCLUSIONS

The new CMRD method was used to test B^+, P^+, and As^+ (with and without oxide) ion-implanted Si wafers at 100 keV in the low-sensitivity dose range $1\times10^{11}-1\times10^{13}$ ions/cm^2. In view of the well-known fact[5,7] that conventional photothermal probes exhibit low sensitivity to dose in this range, it was found that CMRD can significantly enhance the dose resolution of PTR curves from P^+ and B^+ ion-implanted wafers. Comparative conventional square-wave frequency scans were found to be totally or partially unable to resolve the dose. CMRD advantages occur due to effective suppression of signal background and noise levels. It was also established that the pulse separation increment $\delta\Delta$ is a crucial resolution parameter, because it controls the degree of suppression of the instrumental signal and noise baseline levels of the technique.

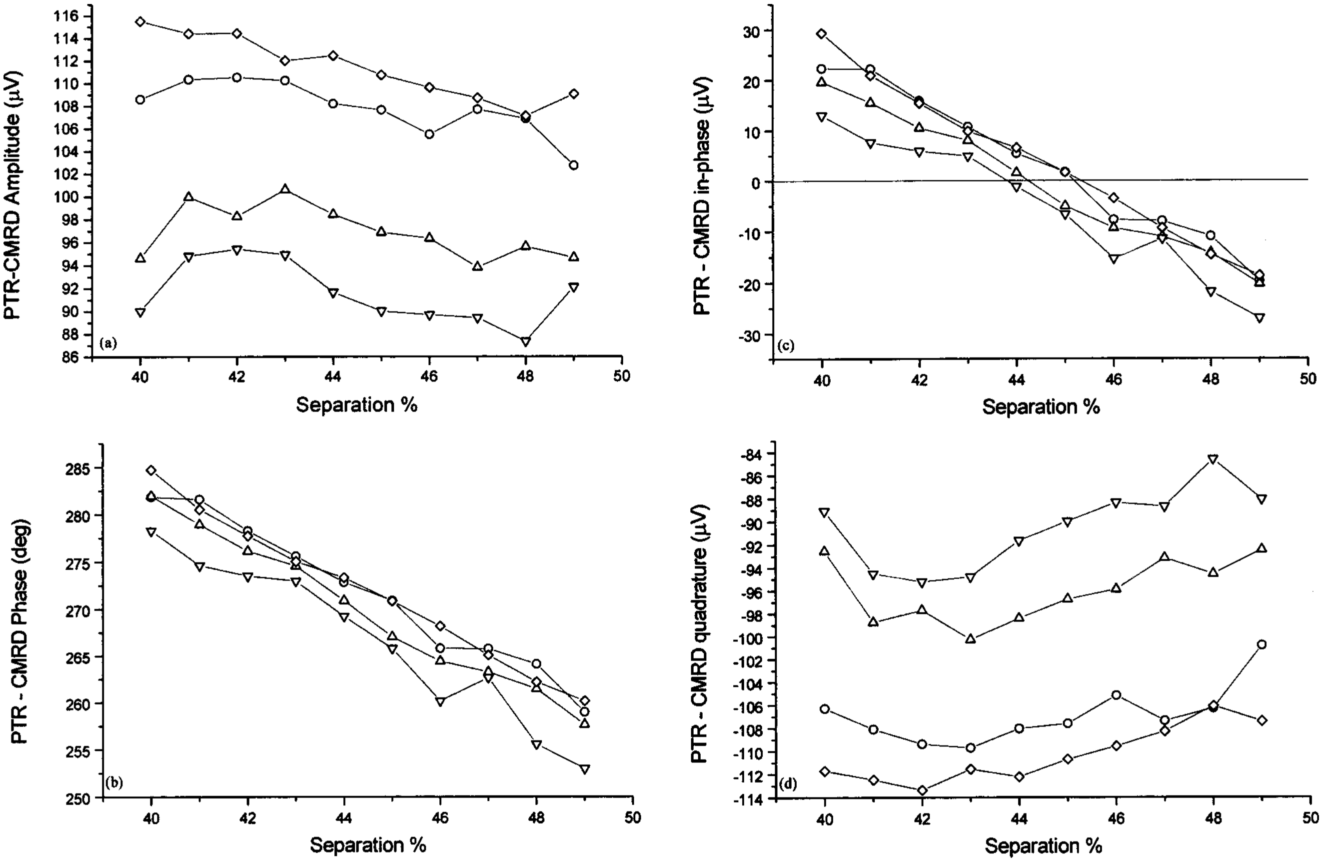

FIG. 5. High-resolution PTR-CMRD amplitude (a); phase (b); IP (c); and Q (d) signals from the P^+-implanted wafers vs center-to-center pulse separation Δ (%). Doses (ions/cm^2): (○) 4×10^{11}; (△) 1×10^{12}; (▽) 4×10^{12}; and (◇) 1×10^{13}. Pulse separation increment $\delta\Delta = 1\%$.

In this work, a methodology to characterize Si wafers with small differences in ion implantation dose was used. A better signal resolution was obtained when compared to conventional single-ended techniques. The differential action has the effect of suppressing the signal baseline. Thus, the instrumental sensitivity is not compromised by the high level signal baseline and can easily match the level of small signal variations introduced by slightly different materials.

ACKNOWLEDGMENTS

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