Infrared photothermal radiometric deep-level transient spectroscopy of shallow B^+ dopant states in *p*-Si

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Infrared photothermal radiometric deep-level transient spectroscopy (PTR-DLTS) has been applied to noncontact diagnostics of a *p*-Si wafer. Both negative and positive peaks in the PTR-DLTS signal temperature scans have been detected. A behavior consistent with photoinjected carrier lifetime enhancement due to the thermal filling of B^+ dopant levels in the band gap has been observed. The activation energies of 43 meV (negative peaks) and 60 meV (positive peaks) have been extracted from the corresponding Arrhenius plots. © *1997 American Institute of Physics.*
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In this letter we report the results of application of the recently introduced infrared photothermal deep-level transient spectroscopy (PTR-DLTS)[1,2] to electronic level diagnostics in silicon. This new technique is based on the rate-window detection principle[3] combined with wafer temperature ramping. The motivation for introducing the PTR-DLTS methodology was the limited availability and restrictive character of existing techniques, such as the laser microwave[4] and the surface photovoltage[5] deep-level transient spectroscopies. Several advantages of the new method over existing technologies—high spectral peak separation, high spatial resolution and no need for electrical contacts—have been demonstrated recently in PTR-DLTS applications to noncontact measurements of deep impurity levels in GaAs and characterization of SiO_2/Si MOS capacitor structures.[1,2,6] In this letter we discuss the PTR-DLTS detection of shallow impurity levels in high-quality Si wafers.

The PTR-DLTS instrumentation setup used in the present study was similar to those described previously.[1,6] An Ar^+ laser emitting $\sim$1 W at 514 nm was used as an excitation source. The modulated square waveform of the laser-beam intensity was controlled by an acousto-optic modulator. The resulting infrared radiation emitted from the sample surface was collected by two off-axis paraboloidal mirrors and detected using a liquid N_2-cooled photoconductive mercury–cadmium–telluride (MCT) detector with a detection bandwidth of 2–12 μm. Temperature ramps were introduced by a heater/temperature controller with the entire process being controlled by the computer. Special arrangements of the setup have been made to accommodate the large-size wafers (diameter 10 cm). The heating system was capable of varying and maintaining the sample temperature up to 473 K with $\pm 0.5°$ precision. A high-quality FZ *p*-Si wafer (thickness 525 μm, diameter 10 cm) doped with boron to the resistivity of 10–15 Ω cm was studied in several locations across the surface.

The PTR frequency-domain (PTR-FD) method supplemented with a finite-thickness, simultaneous amplitude-and-phase fitting algorithm,[7] was used to determine the carrier lifetime (τ) and the surface recombination velocity (s). The modulation frequency range used for the PTR-FD scans was 100 Hz–125 kHz with the lower limit chosen so as to prevent the thermal component from dominating the PTR signal.[8] The two-parameter fitting of the corresponding PTR-FD frequency responses yielded $\tau = 350\ \mu$s and $s = 210$ cm/s at 300 K.

The PTR-DLTS temperature scans of the Si wafer were performed with fixed ratio of the pulse duration (τ_p) to the pulse repetition period (T_0) (duty cycle), equal to 50%. The PTR-DLTS amplitude, phase, quadrature (Q), and in-phase (IP) components were recorded as a function of sample temperature at various T_0. Figure 1 represents some of these PTR-DLTS spectra obtained with $T_0 = 90\ \mu$s. As has been found in our previous studies of Si-based structures,[6] the PTR-DLTS phase temperature dependencies (Fig. 2) are very important and more sensitive to the presence of the DLTS peaks than those of the amplitude, in-phase, or

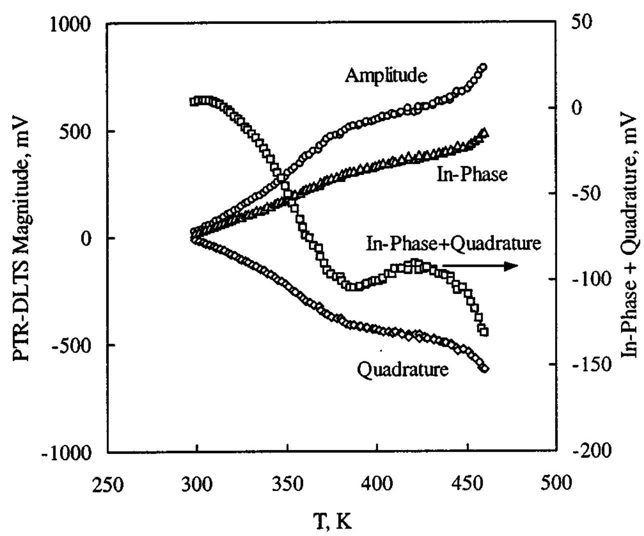

FIG. 1. PTR-DLTS amplitude, in-phase (IP) component, quadrature (Q) component, and combined IP+Q spectra of FZ *p*-Si wafer obtained with the pulse repetition period $T_0 = 90\ \mu$s and duty cycle $\tau_p/T_0 = 50\%$.

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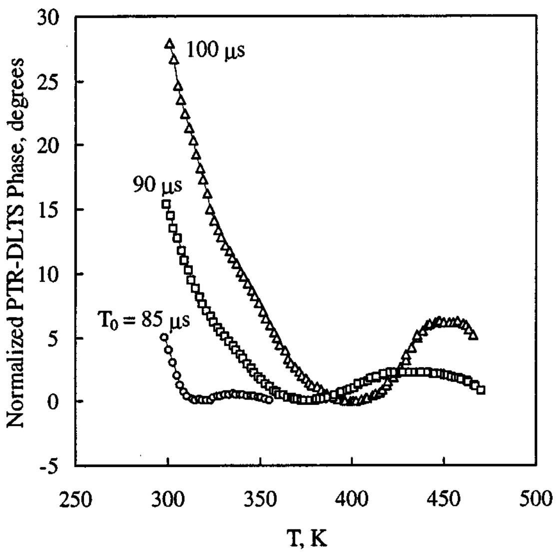

FIG. 2. Normalized PTR-DLTS phase spectra of FZ *p*-Si wafer with various pulse repetition periods (T_0). Duty cycle 50%. Only the part of each spectrum close to two extremes is shown.

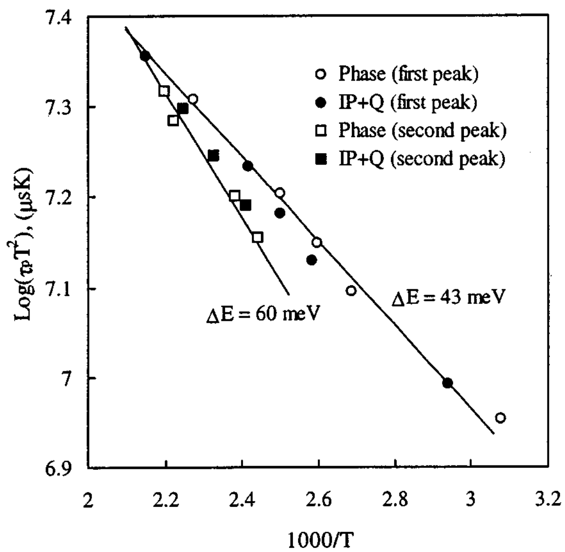

FIG. 3. Arrhenius plots of the lifetimes extracted from the PTR-DLTS phase and IP+Q peaks and calculated energy levels.

quadrature components of the signal. Neither the in-phase, nor the quadrature component temperature dependencies alone exhibited well-defined extrema in the temperature/repetition period range used (Fig. 1). However, the combined IP+Q experimental parameter was found to possess a high temperature peak resolution and was as sensitive as the PTR-DLTS phase. Both the phase and IP+Q peaks were reproducible in several different locations across the wafer and were both considered as measures of the temperature dependence of the carrier lifetime in the sample.

In contrast to our previous measurements of the SiO_2/Si interfaces where only negative PTR-DLTS phase peaks were detected,[6] in the case of FZ *p*-Si the negative peaks in the phase and IP+Q temperature dependencies are followed by positive extrema (Figs. 1 and 2). The lifetime τ_p which was assumed to be proportional to T_0 $[\tau_p(T_m)=\eta T_0]$ where T_m is the PTR-DLTS peak temperature, was found to increase with increasing temperature for both the negative and positive peaks in the phase and IP+Q scans as T_m shifted to higher temperatures with increasing T_0.

The Arrhenius plots of the PTR-DLTS lifetimes and the calculated activation energies for both the first (negative) and the second (positive) peaks in the phase and IP+Q temperature dependencies are presented in Fig. 3. It has been found that both these Arrhenius plots are single exponential, indicating a single trap. The value of $\Delta E=43\pm 2$ meV was found for the negative peaks both in the PTR-DLTS phase and the IP+Q, while the same analysis yielded $\Delta E=60\pm 3$ meV for the corresponding positive peaks. Although the positive peaks were observed in a narrower temperature/repetition period interval than the negative ones, they were reproducible in all tested locations across the wafer. The correlation between the PTR-DLTS phase and the IP+Q Arrhenius-plot data was found to be very good with respect to activation energy values as shown in Fig. 3.

The activation energies obtained from the phase and IP+Q data signal channels can be attributed to shallow electronic traps above the valence band and below the conduction band, respectively. The activation energy of 43 meV can be assigned to the substitutional acceptor (boron, $\Delta E=44.5$ meV above the valence band,[9]) while the value of $\Delta E=60$ meV is close to that reported for the double thermal donor ($\Delta E=61$ meV below the conduction band,[10]). These relatively low activation energies were the reason for which the PTR-FD frequency responses measured at various temperatures exhibited small thermal shifts. Nevertheless, the activation energies of 44. 5 and 60 meV are greater than the thermal quantum k_BT (26 meV at room temperature and 41 meV at 473 K), and thus can be measured by the PTR technique in the $300\ K\leq T\leq 473\ K$ range. In this temperature range the thermal occupation probability of the dopant levels changes greatly. It appears that PTR-FD is not as sensitive to minute lifetime variations with temperature associated with small activation energies, whereas PTR-DLTS which is capable of a higher signal-to-noise ratio,[11] is more sensitive, and can measure such variations.

In conclusion, the foregoing results show the ability of the PTR-DLTS technique to detect shallow doping levels in Si, including the B^+ state in *p*-Si.

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