Infrared photothermal radiometry of deep subsurface defects in semiconductor materials

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Photothermal radiometry (PTR) signals obtained with a highly focused laser beam, were used to obtain amplitude and phase PTR two-dimensional and three-dimensional images of a high-resistivity Si wafer with a mechanical damage on the backsurface, probed from the front (intact) surface. The frequency chosen was 5 kHz, corresponding to an optimal phase resolution of the defect. It is shown that the position of the underlying damage is well resolved in both images, with the phase image showing the expected higher sensitivity in terms of a *greater extent of the damage region* compared to the amplitude image. The results indicate that the change in carrier lifetime is the major contrast mechanism which can thus be calibrated and labeled as a free-carrier recombination lifetime image (under the same surface recombination conditions). [DOI: 10.1063/1.1524006]

I. INTRODUCTION

The nondestructive, nonintrusive evaluation of semiconductor materials has been of common interest to both scientists and engineers since the beginning of the electronic era. In recent years, the evaluation of semiconductors by means of photothermal methods has attracted particular attention, owing to the nondestructive and noncontact character of these techniques. Among photothermal methods,[1] laser photothermal radiometry (PTR) occupies an increasingly important position.[2] In comparison with other photothermal techniques, PTR has been shown to possess distinct advantages, such as remote *in situ* evaluation and optimal sensitivity to the electronic transport properties of the laser photoexcited material.[3] Using two information channels, the PTR amplitude and phase signals obtained with a highly focused laser beam, and recently developed theoretical[4] and computational techniques,[5] one can obtain electronic transport parameters of Si wafers, including the carrier recombination lifetime, τ, the minority carrier diffusion coefficient, D_n, or D_p, the carrier diffusion length, L_D, the front surface recombination velocity, S_1, as well as the thermal diffusivity, α.

Physically, the signal generation process can be described as follows. Upon impinging on a semiconductor surface, an intensity-modulated laser beam simultaneously produces direct lattice heating due to absorption, as well as a modulation in the free photoexcited carrier density (a carrier diffusion wave),[6] provided the photon energy is greater than the band gap energy. The modulated photoexcited free carrier density profile depends on the laser fluence and on the electronic properties of the material in the vicinity of the laser beam. If a wide-bandwidth infrared (IR) detector, such as mercury–cadmium–telluride (HgCdTe) (MCT), is focused on a laser photoexcited spot of the sample, a *superposition* of IR radiative emissions from the excited region may be measured. Unlike conventional photoluminescence, this IR radiation is mainly due to the optical de-excitation of photoexcited carriers, with the simultaneous emission of an infrared photon within the blackbody (Planck) spectral range.[3] In other words, each de-exciting carrier acts like a Planck radiator. The collected signal is the vector sum of this depth-integrated radiation, diffusely emitted by the photogenerated free-carrier plasma-wave density, plus the conventional modulated IR radiation (thermal wave), generated by direct heating due to lattice absorption of the incident laser radiation, and by delayed recombination-lifetime-controlled heating due to nonradiative de-excitations of carriers.[4] The PTR signal can be written as follows:

$$S_{PTR}=S_{th}+S_{pl},$$

where S_{th} is the thermal contribution and S_{pl} is the plasma contribution to the total PTR signal. A detailed three-dimensional (3D) computational model has been published elsewhere.[5]

The signal dependence on the depth integral of the carrier density provides an important diagnostic mechanism for PTR, which thus carries information on carrier diffusion and

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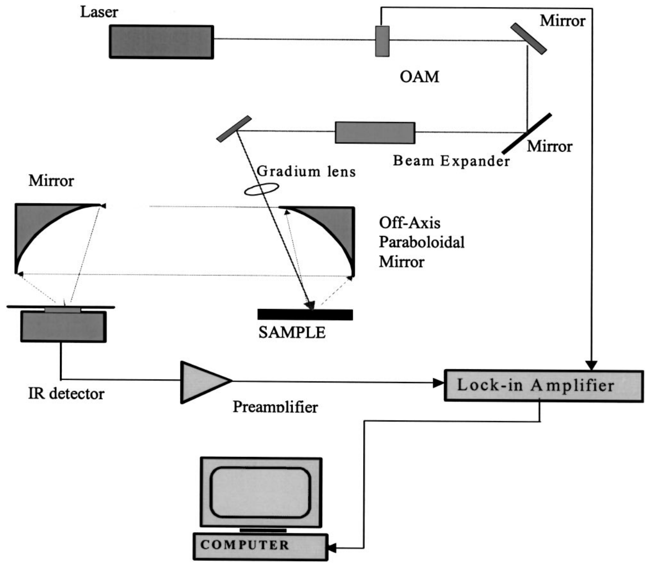

FIG. 1. PTR experimental setup.

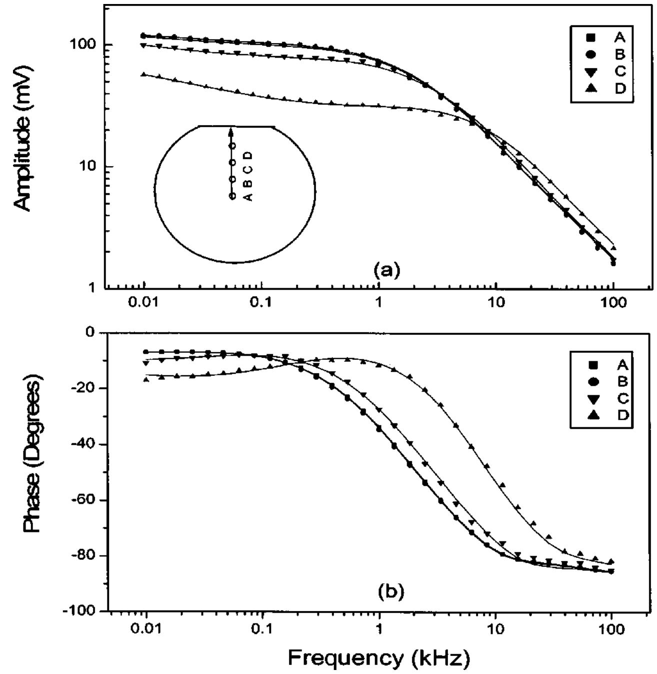

FIG. 2. PTR amplitude (a) and phase (b) for four positions located along the surface.

recombination mechanisms. In typical-quality industrial Si wafers it turns out that the major advantage of PTR over other photothermal methods, including the commercially widely used photomodulated thermoreflectance technique, is the almost complete domination over the thermal-wave response of the signal by the electronic plasma-wave component at all modulation frequencies (Hz–MHz).[7] Therefore, PTR appears to be ideally suitable as a diagnostic technology in assessing the electronic quality of semiconductor substrates and processed wafers. In this work applications of the PTR method for inspection of subsurface defects of silicon wafers will be presented.

II. EXPERIMENTAL SETUP

The instrumental configuration used for frequency scans and thermoelectronic imaging of silicon wafers is shown in Fig. 1 and has been described in more detail elsewhere.[4,5,8] The spot size of the exciting beam was 50 μm. The beam size was estimated using a charge coupled device camera and optical scan measurements through a 5 μm pinhole. The laser power on the silicon wafer was about 20 mW. The excitation beam was modulated from 10 Hz to 100 kHz via an acousto-optic modulator. The IR emission was collected by two collimating off-axis paraboloidal mirrors and was focused onto a liquid-nitrogen-cooled HgCdTe (MCT) IR detector with spectral response between 2 and 12 μm. The PTR signal from the amplifier was fed into a lock-in amplifier and was processed by a personal computer.

Radiometric images were generated using a scanning system that used micrometric stages. These images are PTR amplitude and phase scans at a fixed laser-beam-intensity modulation frequency. In recent work we have shown that the amplitude scales linearly with the recombination lifetime in some ranges of parameters (see Fig. 2).[5,8,9] Therefore, an $x-y$ amplitude scan of the Si substrate (with or without the presence of oxide) when it is properly calibrated in units of microseconds, yields, in principle, a recombination lifetime image of the scanned region. Such a radiometric image has been called a "*thermoelectronic image*," or "*thermoelectronic scan*."

Four positions along the radial direction were measured perpendicular to the flat for a high-resistivity *p*-Si (100) wafer: at the center-point (A); at 1.8 cm (B); at 3.6 cm (C); and at 5.4 cm from center (D); see inset in Fig. 2(a). In Fig. 2 the solid symbols represent the experimental values while the solid lines represent the best-fitted theoretical curve for each radial position using the 3D computational model published previously.[5] These results indicate that there is a direct relation between PTR signal amplitudes and lifetime values as expected from simulations.[5] When the PTR signal increases, so does the lifetime. A plot of this relationship for a high resistivity silicon wafer is shown in Fig. 3. This essentially linear relationship can be used as a rapid wafer inspection method, or for the nondestructive evaluation of industrial silicon wafers through scanning lifetime imaging. The front surface recombination velocities were also obtained for the same positions along the radial direction using the same 3D computational model. These velocities are inversely correlated to the carrier lifetime shown in Fig. 3. For simplicity we selected the lifetime in our discussion since it is directly proportional to the amplitude of the PTR signal.

Figure 4 shows the PTR amplitude (a) and phase (b) of two points located in the region when the mechanical damage was performed: one point is located at the front surface and the other point is located at the backsurface, before (curve No. 1) and after (curve No. 2) the mechanical damage. In the case of the lifetime, it is an effective lifetime (surface and bulk) changes in the bulk lifetime, which are reflected in the effective value. The sensitivity exhibited in the amplitude and phase signals demonstrates that this technique is able to monitor mechanical damage produced deep

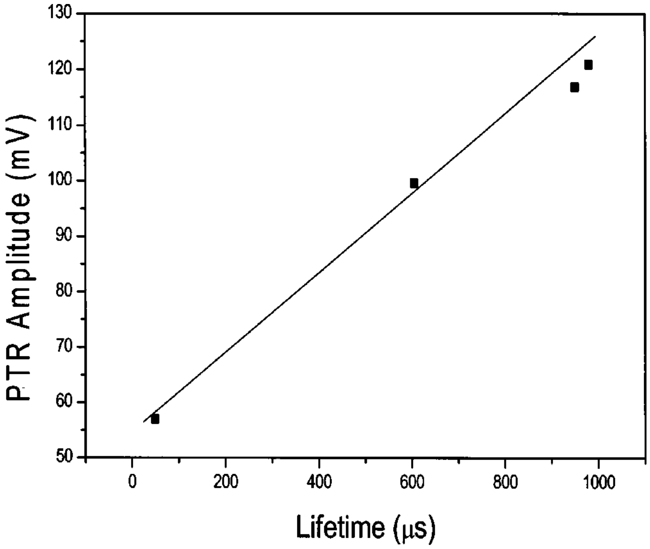

FIG. 3. Relationship between PTR amplitude and lifetime.

inside the bulk of processed silicon wafers through their effects of damage on the photoexcited carrier diffusion wave.

Based on the linear relationship shown in Fig. 3, Fig. 5 shows PTR amplitude (a) and phase (b), two-dimensional and three-dimensional images of the high resistivity Si wafer probed from the front (intact) surface and scanned over the with the inflicted mechanical damage on the backsurface. The frequency chosen was 5 kHz, corresponding to an optimal phase resolution of the defect as indicated in the backsurface frequency scans (see Fig. 4, curve "back 2"). It is

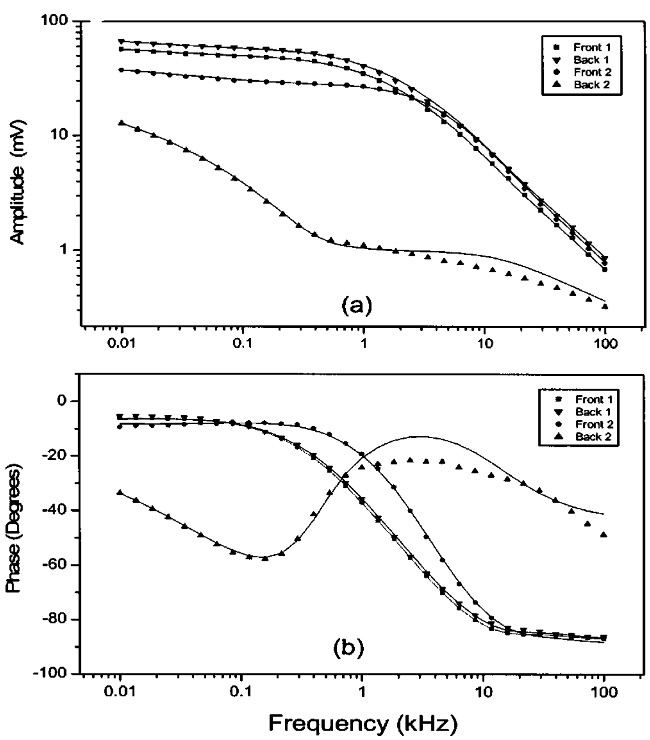

FIG. 4. Frequency scan of PTR amplitude (a) and phase (b) of two points located in the region where the mechanical damage was performed: one point is located at the front surface (intact) and the other point is located at the backsurface (damaged).

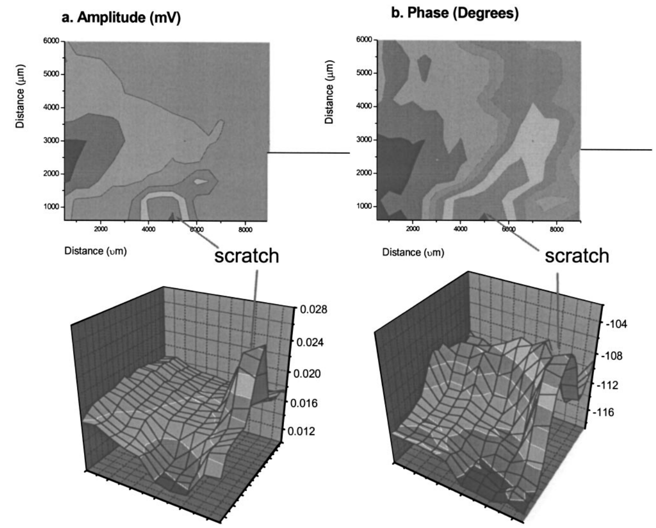

FIG. 5. (a) Amplitude and (b) phase PTR two-dimensional and three-dimensional images of a scratched region of 0.6 cm×1 cm of a high-resistivity Si wafer probed from the front (intact) surface and scanned over the coordinates of the backsurface region with the mechanical damage.

seen that the position of the underlying damage is well resolved in both images, with the phase image showing the expected higher sensitivity in terms of a *greater extent of the damage region* compared to the amplitude image. Based on the linear relationship shown in Fig. 3, we are justified in suggesting that the change in carrier lifetime is the major contrast mechanism in these two-dimensional (2D) and 3D PTR images, which can be calibrated and labeled as a free-carrier recombination lifetime image. It is important to note the long-range effects of the backsurface mechanical damage throughout the bulk. IR radiation from recombination at the damage site reaches the front surface of the wafer where devices are fabricated. It can be captured by the lock-in PTR thermoelectronic imaging, through emission modulation by the harmonically varying IR absorption coefficient across the bulk of the wafer, induced by the carrier diffusion wave oscillation.[10]

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