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Thermally stimulated luminescence in full-size 4H-SiC wafers

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Abstract

We performed non-contact and non-destructive spatially resolved characterization of traps and recombination centres in two-inch-diameter p-type 4H-SiC wafers using thermally stimulated luminescence (TSL) and scanning room temperature photoluminescence (PL). The TSL glow-curve maximum is located at about 190 K for the Al-doped wafers and the TSL spectrum has a maximum at 1.8 eV, which coincides with the spectrum of the 'red' PL band in the same crystal. The TSL intensity exhibits a noticeable inhomogeneity across the wafers. The spatial distribution shows a negative contrast compared to PL maps, indicating a variation of concentration of the TSL centres across the wafer. The origin of the centres is discussed.

1. Introduction

Silicon carbide has superior electronic properties, which make this material an excellent candidate for high-temperature, high-voltage, high-frequency and high-power applications [1]. In addition, SiC is a promising substrate for GaN-based optoelectronic devices as a substitute for sapphire [2]. Despite substantial progress in SiC technology [2, 3], the yield and performance of SiC-based devices is still limited by poor substrate quality and the propagation of defects from the substrate into epitaxial films. Specifically, the dislocations present at a density of $\sim 10^5$ cm^{-2} and micro-pipes degrade the electronic quality of wafers and epilayers. Tracking of the point and extended defects in full-size SiC wafers and epilayers in a non-contact and non-destructive manner is a current need for industry. In this respect, optical characterization offers substantial benefits over electrical techniques since the wafer is kept clean from contacts and therefore available for further analyses and processing.

We explored in this paper the effect of thermally stimulated luminescence (TSL), which has been studied in SiC since the 1960s [4]. The TSL approach was later revisited by various researchers and successfully applied to characterize and identify electron and hole traps in SiC [5, 6]. However, previous TSL results have been reported on small pieces of SiC wafers, rendering the material useless for further spatially resolved analyses and implementation in commercial devices. We report here on a TSL study of commercial grade two-inch-diameter full-size 4H-SiC wafers.

TSL is exhibited in a semiconductor containing electron and/or hole traps. Experimentally, a sample is optically pumped at low temperatures (e.g. 77 K) typically with above-band-gap UV light. As a result of the illumination, traps are filled with electrons and holes and store them, with probability depending primarily on a thermal ionization energy of the trap. Following UV exposure, the optical pump is blocked and a thermal pulse is applied to the sample from a heater attached to the back surface of the wafer. When the temperature is ramped up, the electrons (holes) are released from the traps to the conduction (valence) band and recombine with carriers of the opposite sign stored at the recombination centres. If the recombination is radiative, light is emitted in specific luminescence bands. The intensity of the TSL emission at the initial stage of heating varies according to the equation

$$I_{\mathrm{TSL}} = I_0 \exp(-E_t/kT), \tag{1}$$

where E_t is the thermal ionization energy of the electron (hole) traps, k is Boltzmann's constant, and T is the absolute temperature. Equation (1) allows estimation of the value E_t, which may be a fingerprint of a particular impurity level. Additional trap parameters (frequency factor, capture cross-section and concentration) can be deduced by solving a set of rate equations balancing concentrations of charge traps, of free carriers and recombination centres [7].

2. Experimental details

In this study, single-side-polished two-inch-diameter commercial Al-doped p-type 4H-SiC off-axis Si face (0001) wafers were explored. Full-wafer TSL images in the visible range were obtained using a digital camera realizing a 'snapshot' technique. For detailed analysis, we measured TSL glow curves, which relate the luminescence intensity versus temperature. For these experiments the temperature was ramped from 77 K to room temperature. The two-inch wafer was placed inside a glass Dewar with an optical window on a special holder containing a plane thermofoil heater. Temperature was measured using a thermocouple on the sample holder with readings adjusted to the temperature gradient across the SiC wafer. The temperature ramp could be set between 1 and 10 K s^{-1}. Inhomogeneity of the temperature distribution across the heater during the temperature sweep was within 5%. The temperature was increased linearly with time in the range of the glow curve. For spectral TSL measurements, the luminescence is dispersed by a SPEX500 grating spectrometer coupled with a S1 PMT or liquid-nitrogen-cooled Ge detector. A 200 W Hg arc lamp with 240–420 nm band-pass UV filters was used for optical pumping of the whole wafer. Excitation of the photoluminescence (PL) at temperatures from 4.2 to 300 K is performed using an unfocused CW 325 nm HeCd laser with 55 mW output power.

3. Results

In figure 1(a) we present a 'snapshot' TSL image of the two-inch-thick SiC wafer. The image was obtained after pumping the wafer at 77 K with UV light from the Hg arc lamp followed by heating with a temperature ramp of about 5 K s^{-1}. The TSL image captures the entire glow curve using a 10 s exposure time of the digital camera. The TSL image of the wafer exhibits a pronounced inhomogeneity, which varies by a factor of two between the 'low' and 'high' regions. We confirmed this observation by re-measuring the TSL glow curves

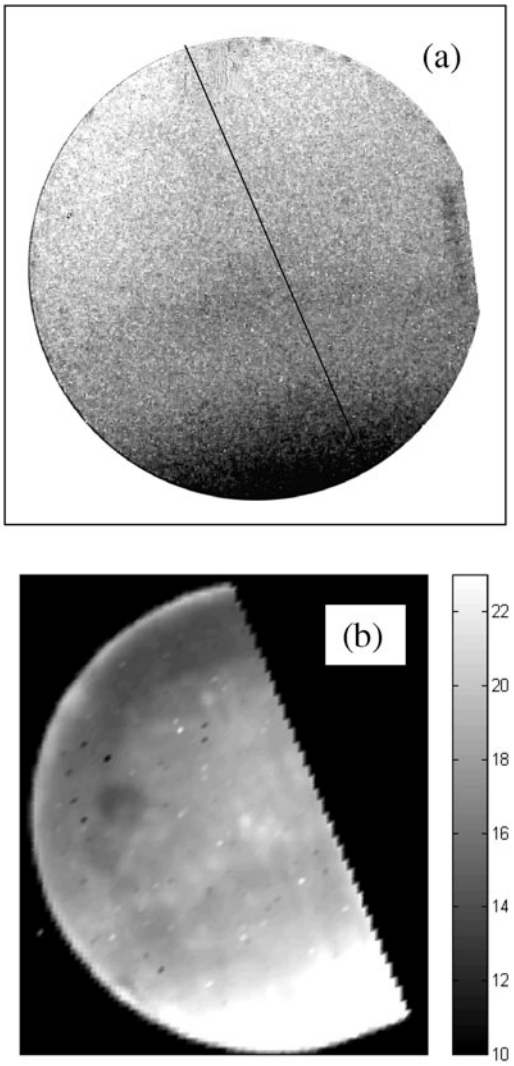

Figure 1. (a) A TSL image of the two-inch-thick SiC wafer showing the luminescence distribution integrated over the entire glow curve in figure 2; (b) room temperature PL mapping at the 'red' 1.8 eV band of the same wafer which was cut along the line in (a) to permit the cryostat insertion. Similar topography shows the PL map of the vanadium-related band at 0.97 eV. Light areas correspond to higher intensity in both TSL and PL. Note that low TSL response corresponds to the highest PL intensity and vice versa.

in the 'low'- and 'high'-intensity areas selectively by shifting the wafer with respect to the entrance slit of the spectrometer. The glow curve corresponding to this TSL image is shown in figure 2. It has a maximum at 190 K and a half-width of 32 K at the temperature ramp of 5.7 K s^{-1}. The maximum position of the glow curve is shifted across the wafer and also versus the temperature ramp within 15 K. The TSL glow curve permits extraction of the E_t-value according to equation (1) applied to the low-temperature part of the peak, as shown in the inset in figure 2. The trap energy estimated from the plot is 174 meV. This simple approach to assessing trap ionization energy using an Arrhenius plot is complemented by results of

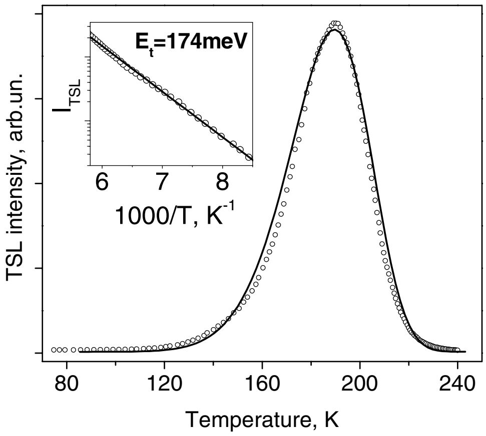

Figure 2. A TSL glow curve of the full-size 4H-SiC wafer (open circles) measured at a 5.7 K s^{-1} temperature ramp. The solid curve is a theoretical fit. The inset shows an Arrhenius plot of the low-temperature part of the glow curve.

the theoretical fit presented by the solid curve in figure 2, similar to analyses performed in [5]. The following parameters were selected for fitting: $E_t = 174$ meV; frequency factor: 7.4×10^{-4} s^{-1}; capture cross-sections of the traps and recombination centres: 1×10^{-19} and 1×10^{-20} cm^2, respectively; concentration of traps: 3.3×10^{17} cm^{-3}; concentration of the recombination centres: 1×10^{15} cm^{-3}. We noticed that the fitting curve relies on the selection of multiple parameters mentioned above. Therefore, a good match with the energy obtained from equation (1) ensures a correct fit.

We performed a spectroscopic study of the TSL glow curve and compared this with the PL spectra measured for small samples cut from the same wafer. The PL spectroscopy was done at various temperatures from 4.2 K to room temperature in the spectral range from 0.7 eV up to 3.25 eV. At low temperatures, the PL spectrum is composed of several individual bands, showing different behaviour at elevated temperatures. The following bands are observed: a 'blue' N–Al donor–acceptor band with a zero-phonon maximum at 3.06 eV and phonon sub-bands [8]; a 'green' band with the maximum at ~2.4 eV; a 'red' band at ~1.8 eV; and infrared bands which contain vanadium-related luminescence with characteristic α- and β-lines at 0.97 and 0.93 eV, respectively [9]. The V-related luminescence at 10 K is illustrated in the inset in figure 3. At room temperature (figure 3), two broad PL bands persist: 'red' and infrared. The latter is a superposition of the V band broadened at room temperature [10] and additional strong IR peaks at 1.06 and 1.11 eV. Our primary concern in this study is the 'red' 1.8 eV luminescence. The reason is that the TSL spectrum shows a good spectral match with the 'red' PL band, as presented in figure 3. On the basis of the spectroscopic study, we may conclude that after optical pumping, the energy is stored by filling deep 174 meV traps and luminescence centres responsible for the 'red' PL band.

Though the luminescence spectrum of the TSL glow curve and that of the 'red' PL band are very close, the spatial distributions of the two signals across the whole SiC wafer are quite different. This is illustrated in figure 1 where a point-by-point mapping of the 'red' band at room temperature (figure 1(b)) is compared with the corresponding area in the TSL image (figure 1(a)). Light areas correspond to higher intensity in both TSL and PL. The topography of the V-related PL map is identical to that of the 'red' band, which indicates that the profile of non-radiative defects is replicated in the PL maps. In areas of low TSL response, both PL

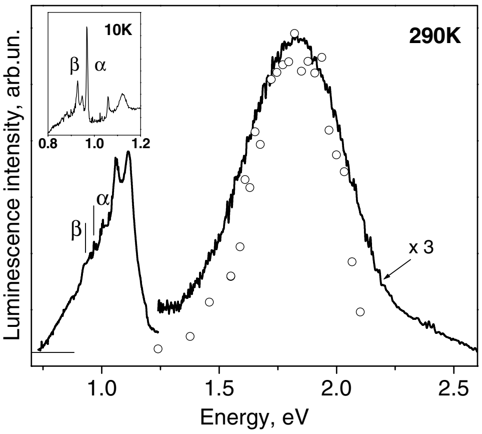

Figure 3. The room temperature PL spectrum of the 'red' and IR bands (solid curve) and the TSL spectrum (open circles). The TSL points present the luminescence integrated over the glow curve with the maximum at 190 K. In the inset, the low-temperature PL spectrum for the range of the vanadium-related band is shown on a matching energy scale.

bands have the highest intensity and vice versa. This difference helps to rule out the possible explanation that a distribution of non-radiative centres is responsible for the TSL profile. In fact, assuming that non-radiative recombination is a primary recombination mechanism at room temperature, this would lead to a similar spatial inhomogeneity of the TSL and other PL bands. This is not observed in the experiment.

4. Discussion

The origin of the defects exhibiting the 190 K TSL peak can be related to Al as a hole trap and the 'red' recombination centre. In fact, the Al ionization energies of 191 and 185 meV in 4H-SiC were determined from the low-temperature PL spectroscopy [8] and TSL analyses [11], respectively. Therefore, the trap activation energy of 174 meV determined here from the TSL glow curve with ~10% accuracy is close to the published values for the Al acceptor. One should keep in mind that the energy of the Al acceptor in SiC is shifting versus doping level and also the degree of compensation [12]. This may explain some deviation of our results from the literature data in terms of the ionization energy.

A few details of the TSL in our samples should be emphasized.

(1) Only negatively charged acceptors (Al^-), which appear due to compensation by shallow donors such as nitrogen, and 'red' recombination centres, can trap the holes generated by UV light at low temperatures.
(2) The concentration of Al^- traps at thermal equilibrium is exponentially reduced from room temperature to 77 K as a result of the Fermi level shift and freezing out of free holes at deep Al acceptors. Therefore, UV-generated holes at 77 K are trapped by Al^- left over in the crystal at 77 K because of compensation. This will transfer traps to the Al^0 state.
(3) Concurrently, after UV pumping the electrons are captured at the 'red' recombination centres. When the distance between filled hole and electron traps is larger than the Bohr radius of a shallowest defect, a direct recombination of the trapped electron and hole has a low probability because the overlapping of the wavefunctions is negligible. A lack of free holes at 77 K additionally promotes the deep donors to hold electrons after UV pumping.

Therefore, the TSL profile shows a distribution of the ‘red’ luminescence centres across the wafer rather than the Al acceptors.

(4) A reverse contrast between the TSL image and the ‘red’ PL map in figure 1 is anticipated if non-radiative centres are distributed similarly to the ‘red’ centres across the wafer. In the PL case, non-equilibrium electrons and holes can be captured sequentially by non-radiative centres, which reduce the PL output. In the TSL, the lack of free electrons determines that the holes released to the valence band from the Al traps are preferably captured by the ‘red’ PL centres. The reason is that non-radiative defects will have a reduced hole capture cross-section in the TSL compared to the PL because of the different charge state.

In conclusion, we have performed rapid, non-destructive TSL characterization of the defect distribution in full-size two-inch-thick SiC wafers. A noticeable inhomogeneity of the ‘red’ TSL glow curve with a maximum at 190 K is observed, which shows a reverse contrast to the maps of the ‘red’ and infrared PL. The TSL topography is explained as an inhomogeneous profile of ‘red’ luminescence centres across the wafer, rather than a distribution of non-radiative defects. We suggest that non-contact and non-destructive TSL diagnostics on full-size SiC wafers can provide a complimentary in-line/off-line tool for ‘snapshot’ quality control of commercial grade material.

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