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Charge-sensitive deep level transient spectroscopy of helium-ion-irradiated silicon, as-irradiated and after thermal annealing*

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Electrically active defects in the phosphor-doped single-crystal silicon, induced by helium-ion irradiation under thermal annealing, have been investigated. Isothermal charge-sensitive deep-level transient spectroscopy was employed to study the activation energy and capture cross-section of helium-induced defects in silicon samples. It was shown that the activation energy levels produced by helium-ion irradiation first increased with increasing annealing temperature, with the maximum value of the activation energy occurring at 873 K, and reduced with further increase of the annealing temperature. The energy levels of defects in the samples annealed at 873 and 1073 K are found to be located near the mid-forbidden energy gap level so that they can act as thermally stable carrier recombination centres.

Keywords: helium-ion irradiation, defect activation energy, charge-sensitive deep level transient spectroscopy

PACC: 6180, 7155, 6170A

1. Introduction

Understanding the structure, formation and evolution of He-induced defects in semiconductors is important in many applicable fields.[1−3] For instance, He-ion irradiation on Si can become a powerful tool to control the carrier lifetime in Si power devices,[4,5] because the irradiation-induced point defects can act as carrier recombination centres in Si. This has the advantage of producing a nonuniform depth distribution of the recombination centres, as compared with the gold diffusion and electron irradiation. So far, there have been a number of articles devoted in the study of the electrical and structural characteristics of defects in Si after He-ion irradiation.[3,6−9] Conventional capacity-sensitive deep-level transient spectroscopy (C-DLTS) was used to investigate the Au-Schottky diodes at temperatures from 80 to 420 K to detect the electrically active energy levels introduced by the He-ion irradiation and subsequent annealing. However, there are fewer studies on the activation energy levels of defects induced by He-ion irradiation and subsequent thermal annealing by using charge-sensitive deep level transient spectroscopy (Q-DLTS).

In this paper, the activation energy levels of defects produced by He-ion irradiation were investigated by Q-DLTS, with an emphasis on their behaviour related with subsequent annealing.

2. Experimental procedure

2.1. Sample preparation

We used [100] oriented Czochralski-grown Si (Cz-Si) wafers with phosphorus, oxygen and carbon concentrations of 9×10^{15}P/cm^3, 1×10^{18}O/cm^3 and 2×10^{16}C/cm^3, respectively. The samples were irradiated by 15 keV He-ion at nominal room temperature at a fluence of 2×10^{16} cm^{-2} and subsequently annealed at several temperatures from 523 to 1073 K in vacuum for 30 min. For the Q-DLTS measurements, Schottky diodes with a diameter of 2 mm were fabricated as follows. Au was evaporated onto the front surface of the samples at a pressure of about 5×10^{-4} Pa used as Schottky electrodes. The backside was evaporated with Al used as ohmic contacts. The distance of the two electrodes is 0.5 mm.

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2.2. Charge-sensitive deep-level transient spectroscopy

The isothermal Q-DLTS is used to measure the activation energy and capture cross-section of He-irradiation-induced deep levels. Q-DLTS isothermal method was described in Refs.[10, 11]. In comparison to the widely used C-DLTS method,[12,13] the characteristics of trapped charge transient process are measured using the Q-DLTS method after cycle bias pulse application. The cycle DLTS algorithm used in our isothermal Q-DLTS method is different from that proposed in Ref.[14]. According to a traditional algorithm, the time period of ΔC measurement $\Delta t = t_2 - t_1$, where t_1 and t_2 are the times counted from the beginning of the discharge, is kept constant while the sample temperature is scanned to obtain the DLTS spectrum. An alternative algorithm used in the present article obtains the spectrum by scanning the rate window $t_m = (t_2 - t_1)/\ln(t_2/t_1)$, while keeping the temperature of the sample constant. Q-DLTS signals from this apparatus can be written as $\Delta Q = Q(t_2) - Q(t_1)$. If assuming that the charge emission from the traps varies exponentially with time while keeping the ratio t_2/t_1 constant, the measured value of the Q-DLTS signal can be written as

$$\begin{aligned}\Delta Q =& Q(t_2) - Q(t_1)\\ =& Q_0[\exp(-e_{\mathrm{p(n)}}t_1) - \exp(-e_{\mathrm{p(n)}}t_2)], \qquad (1)\end{aligned}$$

$$\begin{aligned}Q_0 =& \int_0^\infty Q(t)\mathrm{d}t,\\ e_{\mathrm{p(n)}} =& \sigma \Gamma_{\mathrm{p(n)}} T^2 \exp(-E_a/kT). \qquad (2)\end{aligned}$$

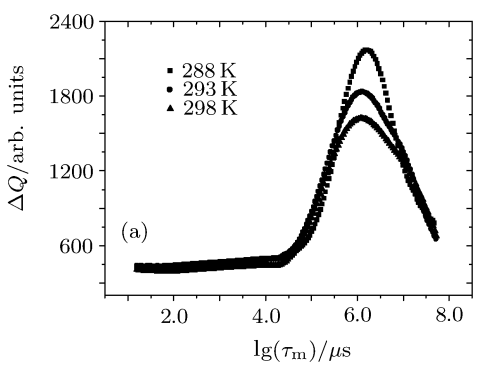
Equation (2) gives the hole(electron) emission rate from acceptor-like(or donor-like) traps, σ is the capture cross-section, $\Gamma_{\mathrm{p(n)}} = 2 \times 3^{1/2}(2\pi/h^2)^{3/2}k^2 m^*_{\mathrm{p(n)}}$, T is absolute temperature, E_a is the activation energy, h is the Plank constant, k is the Boltzmann constant, $m^*_{\mathrm{p(n)}}$ is the effective mass of the hole(electron). The ratio t_2/t_1 in the present measurements is equal to 2 and the electron emission rate of the donor level can be obtained from the Q-DLTS spectrum as $e_\mathrm{p} = \tau_\mathrm{m}^{-1} = \ln 2/t_1$, where τ_m is the value measured at $\Delta Q(\tau_\mathrm{m}) = \Delta Q_\mathrm{max}$. Furthermore, the trapping centre concentration can be obtained from Q-DLTS. $\Delta Q(\tau_\mathrm{m})$ is obtained under isothermal conditions as $N_\mathrm{t} = 4\Delta Q_\mathrm{max} w/(Aq\Delta w^2)$, where A is the electrode area, q is the electron charge, Δw is the depth of the layer in the sample, from which emission of the trapped charge occurs, or the change of the depletion layer width (w) after application of the charging pulse of bias voltage.

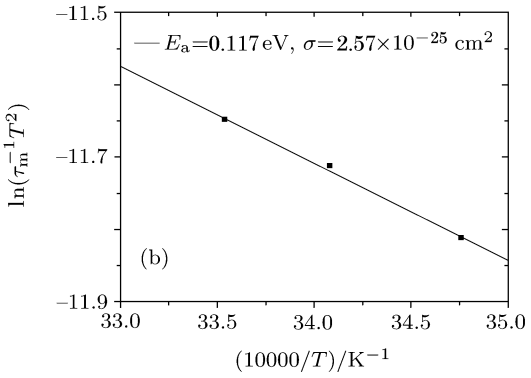
The activation energy E_a and the capture cross-section σ are obtained from Arrhenius plot of $\ln(\tau_\mathrm{m}^{-1}T^{-2})$ against T^{-1} from the measurements of Q-DLTS spectra at several temperatures T (Eq.(2)).

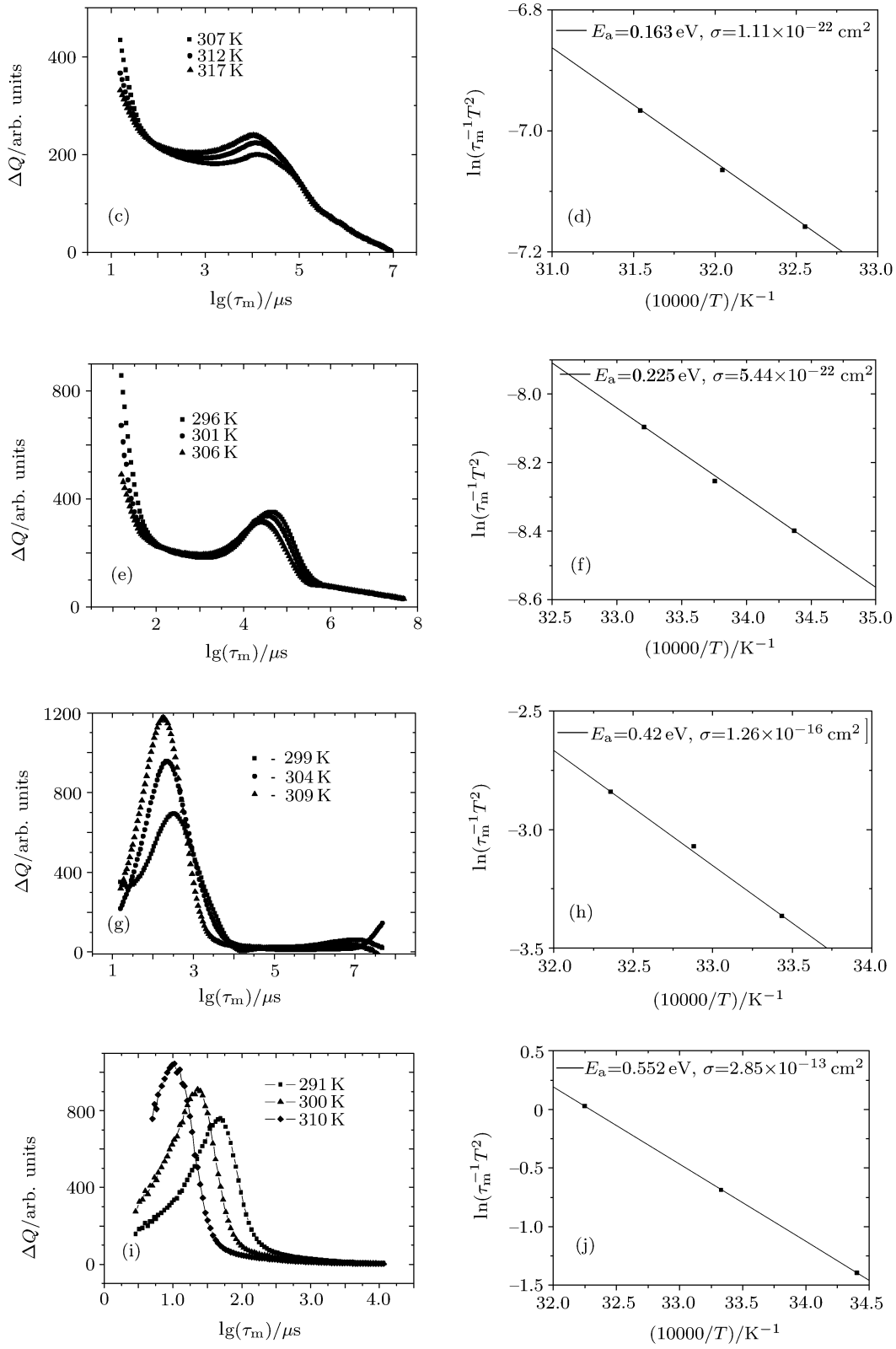
Q-DLTS measurements are carried out in the temperature range from 288 to 317 K and the range of the τ_m from 10^{-6} to 100 s. Q-DLTS spectra are obtained by the computer system automatic system of electrical–physical characterization-03 (ASEC-03).

3. Results and discussion

The Q-DLTS measurements exhibit a peak in Q-DLTS spectra corresponding to helium-induced defects in the Cz-Si (Fig.1). The peak is formed by overcharging of one donor energy level in the forbidden band of silicon.






307 K
312 K
317 K
(c)
ΔQ/arb. units
lg(τm)/μs
Ea=0.163 eV, σ=1.11×10−22 cm2
(d)
ln(τm−1T2)
(10000/T)/K−1
296 K
301 K
306 K
(e)
Ea=0.225 eV, σ=5.44×10−22 cm2
(f)
- 299 K
- 304 K
- 309 K
(g)
Ea=0.42 eV, σ=1.26×10−16 cm2
(h)
291 K
300 K
310 K
(i)
Ea=0.552 eV, σ=2.85×10−13 cm2
(j)

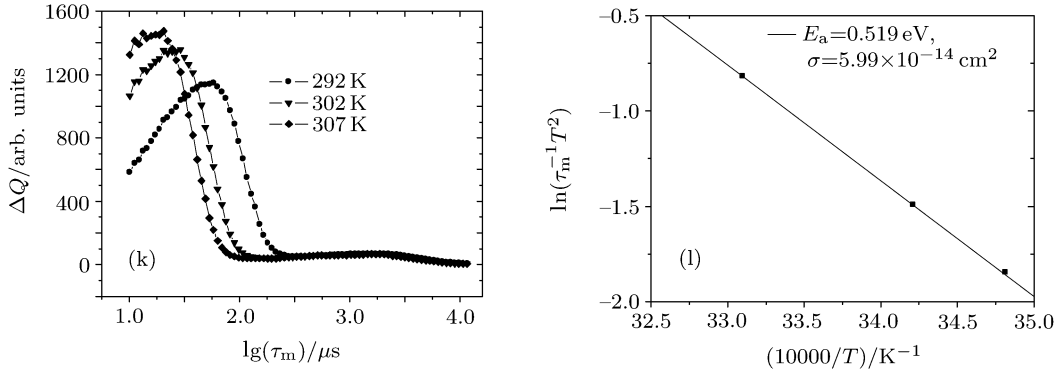


Fig.1. Q-DLTS spectra and the Arrhenius plots of the peaks in the Q-DLTS spectra of the He-ion-irradiated Si: as-irradiated (a, b), subsequently annealed at 523K (c, d); 623K (e, f); 673K (g, h); 873K (i, j); 1073K (k, l). E_a is the activation energy of the defects, and σ is the capture cross-section.

Figure 1 (b, d, f, h, j and l) show the Arrhenius plots for the He-irradiated Cz-Si before and after the isothermal annealing at temperatures ranging from 523 to 1073 K. The He-ion irradiation produces Frenkel pairs in the silicon. Due to the migration and coalescence mechanism,[15,16] He-atoms can combine with vacancy clusters to produce bubbles while self-interstitials can aggregate to form dislocation-type defects near the bubbles after thermal annealing. Simultaneously, it appears that He-atoms will escape from the bubbles and vacancy complexes (cavity or void) are left behind during thermal annealing. In addition, the impurities of the samples will enter vacancies or coalesce with self-interstitials to form defect recombination centres in the forbidden band of Si,[17,18] as shown in Fig.2.

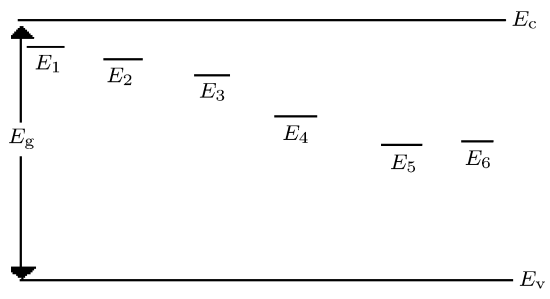


Fig.2. Schematic diagram of the band structure of Cz-Si in a disordered region with different defect energy levels (E_1, E_2, E_3, E_4, E_5 and E_6 denoting different defect energy levels). E_c, E_v and E_g denote the conduction band, valence band and forbidden gap of Cz-Si, respectively.

The different defects in the Si samples are produced by He-ion irradiation and subsequent thermal annealing at different temperatures. For example, there is the main defect of C_s–Si_i–C_s (s: substitute, i: interstitial) in the as-irradiated sample,[19] where the defect activation energy is 0.117 eV (Fig.1(b)). In detail, the ariation of the defects and their activation energy levels with annealing temperature are shown in Table 1. It should be mentioned that the formation of E_5 can be correlated with the annihilation of divacancies and the formation of multivacancies at 873 K, as intensively studied by means of the positron annihilation and numerical calculation.[20,21] Because the diffusion activation energy of O is 2.53 eV in Si, it needs a temperature higher than 1073 K to cause O atoms diffuse obviously in Si.[22] It is indicated that O atoms can diffuse into vacancies to form V_nO_m complex (n: the number of vacancy; m is the number of O) at 1073 K. In particular, since the E_5 and E_6 levels are located near the mid-forbidden energy gap level, the charged states of these levels are electrically neutral, as observed by Raineri *et al.*[5] Because there are dangling bonds on the internal surfaces of cavities in Si,[23] we can find that there are various dangling bonds like electronic states existing on the internal surfaces of the vacancy-type clusters. Since E_5 and E_6 have higher values of activation energy than others and the energy levels are so below the conduction band, they can act as stable carrier recombination centres based on thermodynamics.[24]

Table 1. The activation energy E_a and the capture cross-section σ versus a function of annealing temperature.[25]

defect label	thermal treatment/K	E_a/eV	σ/cm^2	level
E_1	as-irradiated	0.117	2.57×10^{-25}	C_s–Si_i–C_s
E_2	523	0.163	1.11×10^{-22}	V-O
E_3	623	0.225	5.44×10^{-22}	V_2^{-2}
E_4	673	0.42	1.26×10^{-16}	V_2^{-1}
E_5	873	0.552	2.58×10^{-13}	V_n
E_6	1073	0.51	5.99×10^{-14}	V_nO_m

4. Conclusions

Q-DLTS measurements have been performed for the Schottky electrodes to detect active energy levels introduced in Cz-Si by the low-energy, high-dose He-ion irradiation and subsequent annealing. E_5 and E_6 levels were found to be generated near a mid-gap level in the samples annealed at 873 or 1073 K. The behaviours of these defect levels are matched with the annihilation of divacancies and helium-bubble coarsening via the migration and coalescence mechanism. Therefore, we can assume that these energy levels are associated with multivacancy and vacancy-oxygen complexes which are formed by the combination of divacancy clusters and oxygen. The energy levels are probably related to various electronic states, such as dangling bonds existing in the internal surfaces of the clusters and may have higher values of activation energy, and therefore these multivacancies or complexes can act as effective and stable recombination centres.

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