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RELAXATION OF AUGER-EXCITED CARRIERS IN SILICON*

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The near-2-E_g luminescence of highly pure silicon has been studied at liquid helium temperature under high-excitation condition. Besides the luminescence line at 2.27 eV arising from two-electron band-to-band transitions in the electron–hole drops (EHD), a broad, slightly structured spectrum at energies lower than 2 E_g was found. From the intensity and from the shape of this spectrum, it is concluded that it must be referred to the radiative recombination of hot carriers generated by Auger recombination in the EHD. Good agreement is found with a theoretical calculation.

LUMINESCENCE studies in the hot electron region have been done by several authors. Commonly hot electrons were generated by high electric fields in the avalanche breakdown of reverse-biased diode structures.[1–4] The so achieved broad and nearly unstructured spectra are quite well understood[5–7] and can be described by a constant energetic distribution of hot carriers ruled by the parameters E_i-energy for impact ionization – and λ for mean free path. Luminescence from hot carriers generated by light excitation[8] or by Auger-processes[9] was measured in spectral regions where the carriers were nearly thermalized again at the band edge[8] or in the split-off valence band.[9] In that way by luminescence measurements only indirect information about the relaxation processes of hot electrons could be gained.

In the measurements presented here a new way was chosen to measure spectra in the hot electron region in order to get more information about the hot electrons relaxation processes. Hot carriers are generated by Auger-processes in the EHD, so they are nearly monoenergetic at the beginning of their relaxation. The energy relaxation of these carriers forms a stationary carrier distribution now ruled by the partition into different relaxation processes. This carrier distribution in silicon near 1 eV above the band edge could be detected by measuring the luminescence arising from the radiative recombination of these carriers with thermalized ones with opposite sign in the EHD.

The experimental arrangement, in which these measurements were done, consisted of a liquid helium cryostat, a 0.75 m grating monochromator and an S 11 photomultiplier tube. The Si-samples (p-type, 4000 Ω cm) were immersed in liquid helium, which could be pumped to about 2 K. Carriers were excited pulsewise by means of a single-diode GaAs laser, peak power was 5 W, pulse length 1 μsec, and duty cycle 1 per cent. Under these conditions, excited electrons and holes form electron–hole droplets (EHD) in which the carrier density is 3.35×10^{18} cm^{-3}.[10,11] To cut off the excitation light, a Schott filter of type BG 18 was used.

The measured spectrum had the very low intensity of about 1 photon per second after dispersion by the monochromator; in order to detect it, an extremely sensitive photon counting technique had to be used which is described elsewhere.[12] In spite of this sensitive technique, integration times of some weeks were necessary to achieve a spectrum with reasonable signal to noise ratio.

The near-2-E_g spectrum of silicon measured under these conditions is shown in Fig. 1. Besides the

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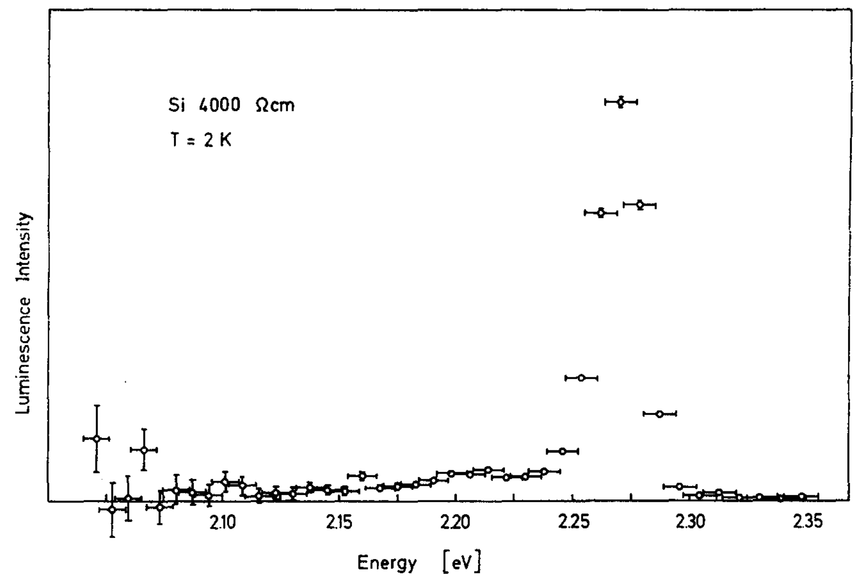

FIG. 1. The near-2-E_g luminescence spectrum of GaAs-laser excited silicon. The relatively intense line at 2.27 eV is caused by two-electron transitions in the EHD.

relatively intense two-electron transitions line at 2.27 eV,[13,14] a weak, slightly structured spectrum at energies lower that 2 E_g arises. A better measurement in this region is shown in Fig. 2, the experimental points are indicated with their error bars. The spectra are corrected for reabsorption and optical response of the detecting system. The process responsible for this spectrum is the following: An electron or a hole is excited to a higher conduction band state or a lower valence band state, respectively, by means of a – as will be shown – phonon-assisted Auger-process. From this state relaxation is possible to the band edge again, and during this relaxation, the electron (hole) has the possibility to recombine radiatively with a thermalized hole (electron). This should be an optical phonon assited process in silicon. Others than the proposed mechanism for the spectrum below 2 E_g can be ruled out. Heating of carriers by other effects should cause no structured spectrum. Two-step excitation should result in luminescence above the 2-E_g line, too. Phonon replicas of the 2-E_g line can be excluded because of energetic and intensity reasons.

The main energy relaxation processes for hot electrons in non-polar semiconductors as silicon and germanium well above the band edge are optical and acoustical deformation potential scattering.[15] For these two processes the relaxation rates are given by[16]

$$\left\langle\frac{\mathrm{d}E}{\mathrm{d}t}\right\rangle_{\mathrm{op}} = -\frac{m_t \cdot m_l^{\frac{1}{2}} \cdot D^2}{2^{\frac{1}{2}} \cdot \pi \cdot \hbar^2 \cdot \rho \cdot (1 - \mathrm{e}^{-x_0})} \cdot [(E - \hbar\omega_0)^{\frac{1}{2}} - \mathrm{e}^{-x_0}(E + \hbar\omega)^{\frac{1}{2}}]$$

and

$$\left\langle\frac{\mathrm{d}E}{\mathrm{d}t}\right\rangle_{\mathrm{ac}} = -\frac{2^{\frac{3}{2}} \cdot m_t^2 \cdot m_l^{\frac{1}{2}} \cdot \Xi_0^2}{\pi \cdot \hbar^4 \cdot \rho} \cdot E^{\frac{3}{2}},$$

where

$$\Xi_0^2 = \left[\frac{2}{3} \cdot \Xi_d^2 + \frac{1}{3} \cdot \frac{m_l}{m_t} \cdot (\Xi_u + \Xi_d)^2\right]$$

and

$$x_0 = \frac{\hbar\omega_0}{K \cdot T}.$$

E is the energy measured with respect to the band edge, D, Ξ_u, Ξ_d are the optical and acoustical deformation potential constants and $\hbar\omega_0$ is the optical phonon energy. Hot holes should relax faster than hot electrons and therefore they play only an unimportant role in the luminescence spectrum. For this reason only hot electrons are considered.

Taking the set of deformation potential constants from Jørgensen, Gram and Meyer,[17] the energy relaxation rates at about 1 eV above the band edge are: $\langle \mathrm{d}E/\mathrm{d}t\rangle_{\mathrm{op}} = 2.7 \times 10^{11}$ eV sec^{-1} and

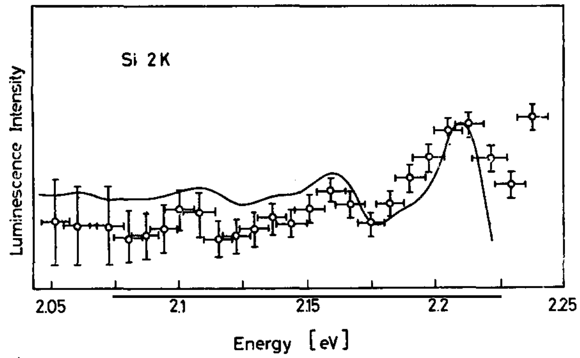

FIG. 2. Luminescence spectrum below $2\,E_g$ with better resolution. The full line gives the theoretically expected shape (ratio of optical to acoustical relaxation rate: 2.7).

$\langle dE/dt \rangle_{ac} = 1.3 \times 10^{11}$ eV sec^{-1}. That results in a ratio of $Q = 2.1$ for the partition into optical and acoustical relaxation processes and in a total relaxation rate of 4×10^{11} eV sec^{-1}. Experimentally the total relaxation rate can be determined by comparing the luminescence intensities of the relaxation spectrum with that of the EHDs E_g line, taking into account radiative and non-radiative lifetimes of the electrons in the EHD[18] and the different reabsorption lengths[19] at the two energies. This calculation leads to an experimental value of 6×10^{11} eV sec^{-1}, which corresponds very well with the theoretical one.

By a computer Monte Carlo treatment the shape of the spectrum to be expected theoretically has been calculated for several values of Q. The best fit, which is shown by the full line in Fig. 2, has been found for a Q-value of about 2.7. That means that optical processes are slightly underestimated by simple deformation potential theory. That the theoretical spectrum does not show the same broadening of the peaks as the experimental one is due to the fact that the calculation has been done in a one-dimensional band-structure and the three-dimensional dispersion of the phonons involved in the Auger-process and in the radiative recombination has not been taken into account.

The energetic fit of the theoretical to the experimental relaxation spectrum gives an estimate for the energy of the phonon involved in the eeh-Auger-process in silicon. If one assumes that the radiative transition is accompanied by a TO phonon, the "Auger Phonon" should have an energy of 9 ± 5 meV. So it should either be a transverse or a longitudinal acoustical phonon. A phononless eeh-Auger-process as proposed by L. Huldt[20] cannot fit the energetic situation.

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Die 2 E_g nahe Lumineszenz von hochreinem Silizium wirde bei Helium-Temperatur im Bereich hoher Anregung untersucht. Außer der Lumineszenzbande bei 2.27 eV, die von Zwei-Elektronen-Band-Band-Übergängen in den Elektron–Loch-Tröpfchen (EHD) herrührt, wurde ein breites, leicht strukturiertes Spektrum bei Energien unterhalb von 2 E_g gefunden. Aus der Intensität und der Form dieses Spektrums wird geschlossen, daß es von der strahlenden Rekombination heißer, durch Auger-Rekombination in den EHD erzeugter Ladungsträger herrührt. Durch eine einfache theoretische Abschätzung lassen sich die experimentellen Daten gut beschreiben.