The cathodoluminescence spectrum of interband transitions in monocrystalline germanium

1993 J. Phys.: Condens. Matter 5 L587

(http://iopscience.iop.org/0953-8984/5/45/001)

J. Phys.: Condens. Matter 5 (1993) L587–L590. Printed in the UK

LETTER TO THE EDITOR

The cathodoluminescence spectrum of interband transitions in monocrystalline germanium

Xu Xiaoliang†, Hao Luyuan†, Xu Kezun†, Yang Bingxin† and Liu Chunrong‡

† Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui 230 027, People's Republic of China

‡ Department of Physics, Anhui University, Hefei, Anhui, 230 000, People's Republic of China

Received 3 August 1993, in final form 24 September 1993

Abstract. The cathodoluminescence spectrum of interband transitions in monocrystalline germanium has been measured in the energy region from 2.6 eV to 4.6 eV. Several new peaks located at 3.2 eV, 3.6 eV, 3.9 eV and 4.3 eV which agree with the theoretical predictions have been obtained. Some discussions of the distortion of the spectrum are also given.

To establish the band structure of a semiconductor it is important to study the spectrum in the wide energy region (1–10 eV) above the intrinsic absorption threshold. Previous studies have concentrated on analysing the reflection spectrum, because it is difficult to measure the emission spectrum due to the intense absorption in the region. The band structures of a series of semiconductors have been successfully calculated using 'local' [1] and 'non-local' [2] EPM (empirical pseudopotential method). The germanium band $E_n(k)$ is shown in figure 1 and the eigenvalues at Γ, X and L are shown in table 1 [2].

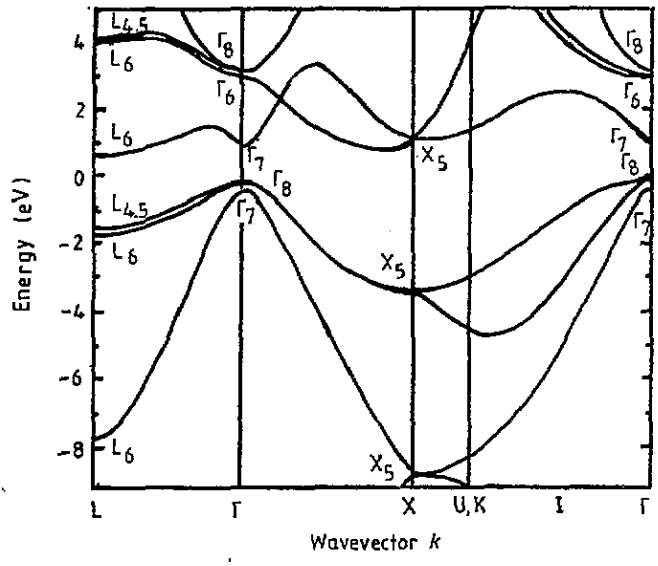

Figure 1. The germanium bandstructure $E_n(k)$ calculated by the pseudopotential method [2].

0953-8984/93/450587+04$07.50

Table 1. Eigenvalues for germanium at Γ, X, and L. Energies are in eV.

Point	Γ					X		L		
Level	Γ_7^v	Γ_8^v	Γ_7^c	Γ_6^c	Γ_8^c	X_5^v	X_5^c	L_6^v	$L_{4,5}^v$	L_6^c
Energies	−0.29	0.00	0.90	3.01	3.22	−3.29	1.16	−1.63	−1.43	0.76

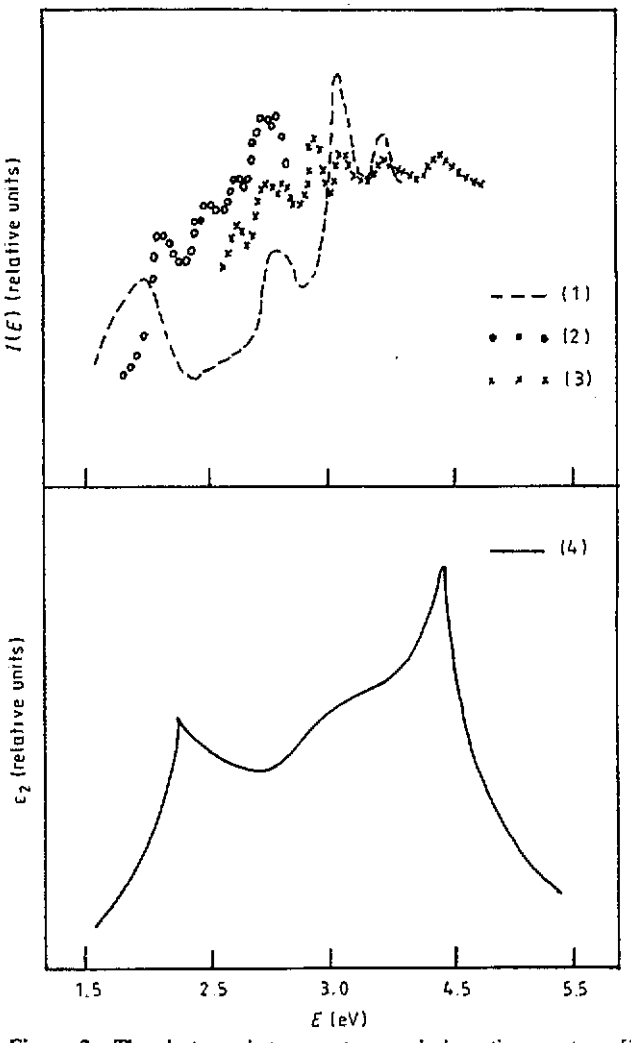

Figure 2. The electron–photon spectrum and absorption spectrum [12] of germanium: (1) theoretical emission spectrum; (2) experimental spectrum obtained for E_p = 200 eV [11]; (3) experimental spectrum obtained for E_p = 4 keV; (4) absorption spectrum ϵ_2.

If a cathode ray is used to impinge on the targets, the radiative transitions from levels E_p (energy of primary electrons) are negligible because at these energies the electron states will decay fairly rapidly. This is the reason why the relative probability of radiative relaxation is low [3–6]. Studies also showed that when values of E_p are much greater than the plasma energy, the cathodoluminescence spectrum represents mainly radiative transitions of electrons and holes created by the cascade of electron–electron and electron–plasmon inelastic collisions [7–10]. On the other hand, Shatalov *et al* [11] indicated that the band

structures would have some changes, because the effect of incident electrons on the target is to distort the bands of free electrons and smooth the Van Hove singularities; the intensity of the singularities then becomes weaker, which leads to a decrease of the photon emission and the creation of some new structures. The same authors also calculated the intensity of the emission spectrum of germanium (see figure 2).

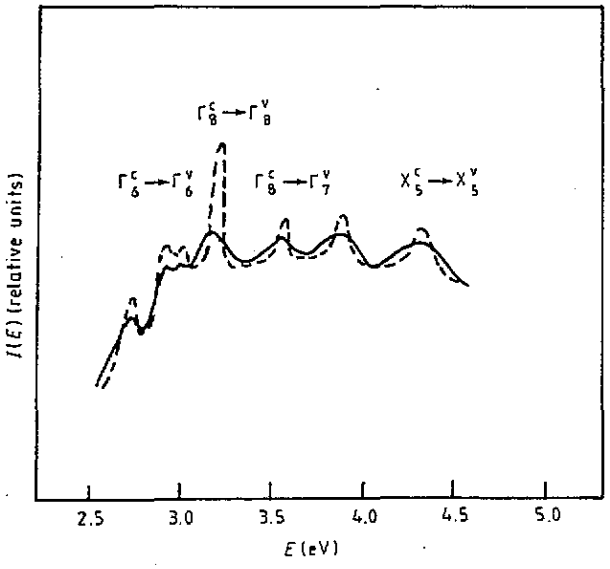

Figure 3. The comparison of electron–photon emission spectra at different irradiation times. The full curve shows the spectrum measured after an extra 30 m of irradiation time.

The cathodoluminescence spectrum of polycrystalline germanium was first measured in the energy region from 1.7 eV to 3.1 eV [11]. A p-type monocrystalline germanium sample was used as a target in our experiment. The surface of the target was cleaned by hydrofluoric acid and the planar orientation was ⟨111⟩. The resistivity was 1.4–1.8 Ω cm and the intensity of the incident electron beam on the target was 10^{-6} A cm^{-2} at an energy of 4 keV. A liquid nitrogen trap was placed between the chamber and the turbo pump, and the working pressure in the system was 10^{-5} Pa. A magnetic coil was used to deflect the electron beam in order to prevent direct optical incidence from the filament impinging on the target. The cathodoluminescence spectrum measured in the energy region from 2.6 eV to 4.6 eV is also shown in figure 2.

From 2.6 eV to 3.1 eV, the experimental curve is in agreement with that of Shatalov *et al* [11]. A main structure at 3.0 eV is identified by the transition between $\Gamma_6^c \rightarrow \Gamma_8^v$ (see figure 1). The spectrum from 3.1 eV to 4.6 eV was the first measurement. Several new peaks at 3.2 eV, 3.6 eV, 3.9 eV and 4.3 eV have been obtained. Two peaks at 3.6 eV and 3.9 eV are fitted to the theoretical curve (see figure 2). Two structures at 3.2 eV and 3.6 eV are in agreement with the results of calculations by Chelikowsky and Cohen [2], corresponding to the transitions $\Gamma_8^c \rightarrow \Gamma_8^v$ and $\Gamma_8^c \rightarrow \Gamma_7^v$.

The structure at 4.3 eV corresponds to the transition in k space near $X_5^c \rightarrow X_5^v$, and the calculation value was 4.45 eV [2]. This red shift can be explained by the dramatic shift in the absorption spectrum of germanium from 4.0 eV to 4.4 eV [12] (see figure 2). The ordinate ϵ_2 is the imaginary part of the dielectric constant, $\epsilon_1 + i\epsilon_2$ which expresses optical absorption in solids.

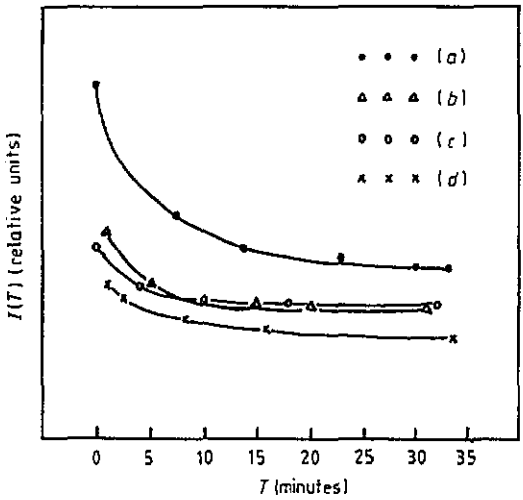

Figure 4. The dependence of cathodoluminescence intensity on the irradiation time at (a) 3.2 eV, (b) 3.6 eV, (c) 3.9 eV and (d) 4.3 eV.

The difference between the theoretical calculations of [2] and [11] is that the distortion of band structure and the smoothing of the Van Hove singularities had been considered in the latter. Our experiment shows that the former theory can also be used to explain the cathodoluminescence spectrum successfully. As a matter of fact, the density of states near the Van Hove singularities is too intensive to be smoothed rapidly, so the transitions corresponding to these singularities still show the properties of the main peak in a certain time of measurement. However, with increasing irradiation time by electron beam, the counting rates at the peaks decrease markedly; this is shown in figure 3. The dependence of cathodoluminescence intensity on the irradiation time at four peaks is shown in figure 4.

Before each new set of data was collected, our sample shelf was rotated so that the electron beam was always incident on a fresh surface of germanium. This was to avoid distortion of the spectrum by irradiation damage.

We would like to thank Professor Xia Shangda and Professor Shi Chaoshu for their constructive advice. The work was supported by the National Natural Science Foundation of China under grant No 19004009.

References

[1] Cohen M L and Bergstresser T K 1966 *Phys. Rev.* **141** 789
[2] Chelikowsky J R and Cohen M L 1976 *Phys. Rev.* B **14** 556
[3] Emerson L C, Birkhoff R D, Anderson V E and Ritchie R H 1973 *Phys. Rev.* B **7** 1978
[4] Spencer and Fano 1954 *Phys. Rev.* **93** 1172
[5] Shatalov V M 1986 *Solid State Commun.* **59** 53
[6] Panczenko O F and Shatalov V M 1987 *Sov. Phys.–JETP* **66** 127
[7] Klyap M P, Kritskii V A, Kulyupin Yu A, Kucherenko Yu N, Pilipchak K N and Pop S S 1984 *Sov. Phys.–JETP* **59** 653
[8] Kulyupin Yu A, Fedosenko A F, Shatalov V M and Shchurenko A I 1984 *JETP Lett.* **40** 1086
[9] Kobzar Yu M, Kulyupin Yu A and Shatalov V M 1986 *Sov. Phys.–Solid State* **28** 1971
[10] Antonov V N, Kobzar Yu M, Kulyupin Yu A, Pilipchak K N, Shatalov V M and Shchurenko A I 1987 *Sov. Phys.–Solid State* **29** 519
[11] Shatalov V M, Panchenko O F, Pilipchak K N and Zolotukhin E V 1989 *Sov. Phys.–Solid State* **31** 712
[12] Philips J C 1973 *Bonds and Bands in Semiconductors* (New York: Academic) ch 7