PHOTOLUMINESCENCE IN HEAVILY DOPED Si AND Ge

J. Wagner, A. Compaan, A. Axmann

To cite this version:

J. Wagner, A. Compaan, A. Axmann. PHOTOLUMINESCENCE IN HEAVILY DOPED Si AND Ge. Journal de Physique Colloques, 1983, 44 (C5), pp.C5-61-C5-64. <10.1051/jphyscol:1983508>. <jpa-00223088>

HAL Id: jpa-00223088
https://hal.archives-ouvertes.fr/jpa-00223088
Submitted on 1 Jan 1983

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
PHOTOLUMINESCENCE IN HEAVILY DOPED Si AND Ge

J. Wagner, A. Compaan* and A. Axmann*

Max-Planck-Institut für Festkörperforschung, Heisenbergstr. 1, 7000 Stuttgart 80, F.R.G.
*Fraunhofer-Institut für Angewandte Festkörperphysik, Eckerstr. 4, 7800 Freiburg, F.R.G.

Résumé - Nous présentons des spectres de photoluminescence à basse température mesurés sur une série d'échantillons de Si et de Ge dopés et implantés en ions lourds. En opérant un recuit laser sur les échantillons implantés, des concentrations de porteurs allant bien au-delà de la limite de solubilité à l'équilibre peuvent être obtenues (jusqu'à $10^{21} \text{ cm}^{-3}$). De ces spectres nous déduisons des informations sur la bande interdite réduite ainsi que sur le remplissage des bandes en fonction de la concentration de porteurs.

Abstract - We report the results of low-temperature photoluminescence measurements on a series of bulk doped and heavily ion implanted Si and Ge samples. By laser annealing of the ion implanted samples carrier concentrations far above the equilibrium solubility limit (up to $10^{21} \text{ cm}^{-3}$) were obtained. From this photoluminescence spectra, information on the reduced band gap and the band filling as a function of carrier concentration is obtained.

The basic physical properties of heavily doped semiconductors are of practical as well as theoretical interest. For bulk doped material the substitutional impurity concentration is limited to $10^{19}$ - $10^{20} \text{ cm}^{-3}$ by the equilibrium solubility limit. It has been shown previously that concentration far above this limit can be obtained by laser annealing of heavily ion implanted material /1/.

We performed photoluminescence studies on both bulk doped and ion implanted Si and Ge samples with carrier concentration up to $10^{21} \text{ cm}^{-3}$. By photoluminescence (PL) experiments the carrier distribution within the conduction or valence band as well as the carrier induced shrinkage of the band gap can be studied via the radiative recombination of photoexcited minority carriers /2,3/.

The ion implanted samples were bombarded with up to $2 \cdot 10^{16} \text{ ions/cm}^2$ and annealed with an XeCl excimer laser /4/. For the PL measurements the samples were cooled by He exchange gas to 5 - 10 K. The luminescence was excited by the 647.1 nm line of a Kr ion laser and analyzed by a 1m double spectrometer and an intrinsic Ge diode.

Fig. 1 shows the results for bulk doped Si:P. In the PL spectrum of the sample with the lowest impurity concentration ($4 \cdot 10^{18} \text{ cm}^{-3}$) four lines are resolved. These are, from higher to lower energies, the no-phonon-transition (NP), the TA and TO momentum conserving phonon assisted replicas and the TO + 0' replica, involving a momentum conserving plus an optical zone center phonon. For increasing impurity concentration the lines become broader and for the heaviest doped samples only the two strongest replicas (NP and TO) can be distinguished. From the excitation density of $=100 \text{ W/cm}^2$ used for recording this spectra it can be concluded that

*Permanent address:
Department of Physics, Cardwell Hall, Kansas State University, Manhattan, Kansas 66506, U.S.A.
we are in the high excitation limit as defined by Parsons /5/. Therefore the luminescence is interpreted as the radiative recombination of electrons from the degenerate conduction band with free photoexcited holes.

Fig. 1 - Photoluminescence of bulk doped Si:P samples at 10 K. The arrows indicate the high energy cutoff edge of the NP-line (\(E_{g,1}\)) and the low energy edge of the TO-replica (\(E_{g,2} - \hbar \omega_{TO}\)).

Fig. 2 - Photoluminescence of bulk doped Si:P samples at 10 K. The arrows indicate the high energy cutoff edge of the NP-line (\(E_{g,1}\)) and the low energy edge of the TO-replica (\(E_{g,2} - \hbar \omega_{TO}\)).

The low energy cut-off of the luminescence line, indicating the energy separation \(E_{g,2}\) at the top of the valence and bottom of the conduction band, exhibits a pronounced shift to lower energies with increasing carrier concentration. The high energy edge \(E_{g,1}\), given by the sum of the band gap \(E_{g,2}\) and the kinetic energy of the carriers, remains approximately constant with increasing impurity concentration.
Fig. 3 - Bandstructure of Ge. The luminescence transitions, possible in heavily doped n-type material, are schematically indicated. The values shown for band separations refer to pure Ge at low temperatures.

The results for Ge:P are summarized in Fig. 2. The sample with the lowest impurity concentration is bulk doped, the more heavily doped ones are ion implanted. The luminescence spectrum, here again originating from band to band transitions, is dominated by the no-phonon contribution /2/. The high energy edge shows a drastic shift to higher energies with increasing carrier concentration. For the heaviest implanted sample (=5 \cdot 10^{20} \text{ cm}^{-3}) the luminescence band extends up to 0.98 eV. This indicates for that carrier concentration a filling of the direct \Gamma_C conduction band minimum and, eventually, also of the higher lying indirect \chi_C minima (see Fig. 3). The corresponding gap energies are 0.89 eV and 0.95 eV for the \Gamma_C to \chi_V (top of the valence band) and \chi_C to \Gamma_V transition respectively, compared to 0.75 eV for the lowest gap involving the indirect L point conduction band minima (\Gamma_L to \chi_V). These values refer to pure Ge at low temperatures. The low energy edge of the PL line could not be resolved due to the cut-off at 1.7 \mu m of the Ge detector used for these experiments.

Only a relatively small number of electrons contribute to the \Gamma_C to \Gamma_V luminescence due to the much lower density of states in the \Gamma_C band minimum compared to the 4-fold degenerated L point minima. But on the other hand the luminescence efficiency is expected to be much higher for this direct transition than for indirect processes. So the luminescence intensity of the direct transition becomes comparable to the one of the indirect \Gamma_C to \Gamma_V recombination. Direct luminescence from the \Gamma_C conduction band minimum has been reported previously for highly photoexcited pure Ge by van Driel et al. /6/. The low temperature PL spectra shown in that paper have strong similarities to the one shown in the present work for the most heavily doped sample.

Comparing the dependence of the optical gap \E_{G,1} on the carrier concentration for n-type Ge and Si a remarkable difference is found. In Ge a pronounced shift to higher energies is observed for increasing dopant concentrations. This shift amounts to \approx 0.25 eV for \approx 5 \cdot 10^{20} \text{ cm}^{-3}, compared to the band gap of pure Ge. In Si in con-
An approximately constant value of $E_{G,1}$ is found up to $1.5 \cdot 10^{20}$ cm$^{-3}$. As pointed out by Mahan/7/ this different behaviour is attributed to two effects. First the effective density of states mass for electrons is a factor of two smaller for Ge than for Si when taking into account the degeneracy of the conduction band. This effect results in a higher kinetic energy in Ge than in Si for a given carrier concentration. Second the reduction of the gap $E_{G,2}$ is larger in Si than in Ge due to the larger Rydberg energy of Si.

In conclusion we have shown that semiconductors extremely heavily doped by ion implantation and laser annealing can be studied by photoluminescence. This study provides valuable information on the filling of higher lying band minima and on the band gap shift as a function of carrier concentration over a much wider range as accessible with bulk doped material.

ACKNOWLEDGEMENTS

We like to thank Prof. M. Cardona for many helpful discussions and Messrs. H. Hirt, M. Siemers and P. Wurster for valuable experimental assistance.

REFERENCES


4. COMPAAN A., CONTRERAS G., CARDONA M. and AXMANN A. (paper, these proceedings).

