B — 3 — 8 Tunable Electro- and Photoluminescence from GaAs Doping Superlattices

K. Ploog, H. Jung, H. Künzel, and P. Ruden

Max-Planck-Institut für Festkörperforschung

D-7000 Stuttgart-80, Federal Republic of Germany

A new type of an artificial periodic semiconductor structure with tunable band gap, the GaAs doping or "NIPI" superlattice, has been grown by molecular beam epitaxy (MBE). The structure consists of a periodic sequence of thin (5<d<300 nm) n(Si)- and p(Be)-doped GaAs layers, possibly separated by intrinsic (i-) layers (Fig. 1a). In this paper we present the results of detailed studies of radiative electron-hole recombination across the tunable indirect energy gap in GaAs doping superlattices of different design parameters. Generation of excess electron-hole pairs has been achieved by photoexcitation leading to tunable photoluminescence and by controlled carrier injection via selective electrodes yielding tunable electroluminescence. These two aspects are of specific importance for future device applications of this new class of semiconductor material.

The unusual electronic properties of GaAs doping superlattices arise from the fact that the space charge potential of the ionized impurities varying in the direction of layer sequence produces a periodic parallel modulation of the energy bands as indicated in Fig. 1b. In non-excited crystals the amplitude of this modulation simply depends on the preselected design parameters, i.e. doping concentration and layer thickness, of the constituent layers of the superlattice. As a result, the energy gap in the layered material is indirect in real space with the electron and hole states spatially separated by half a superlattice period, and the effective energy gap is reduced as compared to the homogeneous host material. The effective spatial separation between electrons and holes has two fascinating consequences for the electronic properties of GaAs doping superlattices: (i) the recombination lifetimes of excess carriers are enhanced by many orders of magnitude over that in homogeneous bulk material, and (ii) the energy gap is no longer a constant material parameter but is tunable by varying the non-equilibrium carrier concentration, since the mobile carriers partly compensate the space charge potential of the fixed ionized impurities.

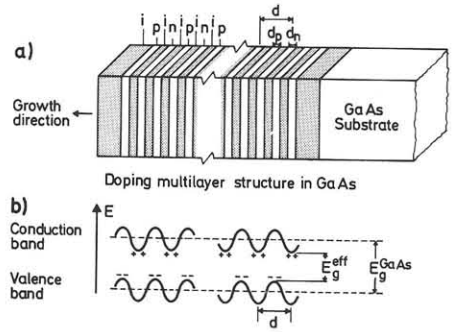

Fig. 1 (a) Schematic illustration of GaAs doping ("NIPI") superlattice; (b) periodic modulation of the conduction and valence band edges.

The luminescence in GaAs doping superlattices arises from recombination of (thermalized) electrons in different occupied conduction subbands with (thermalized) holes in a narrow impurity band located above the valence subbands across the tunable indirect gap, as schematically shown in Fig. 2a. In Fig. 2b four photoluminescence spectra covering the energy range of 1.20 eV<$\hbar\omega$<1.50

eV obtained from a representative sample (# 2432) are shown. The position of the asymmetric luminescence line is shifting strongly as a function of photoexcitation intensity. We observed a similar shift for the electroluminescence peak energy as a function of injection current, when we injected electrons and holes over long distances via selective electrodes. With increasing photoexcitation intensities or injection current densities, resp., the increasing steady state concentration of (spatially separated) excess electrons and holes is screening more and more effectively the bare space charge potential of the ionized impurity atoms. The modulation of the band edges is thus reduced and the effective band gap approaches the gap of bulk GaAs. In addition, the total luminescence intensity increases with excitation on an exponential scale due to the increasing overlap between electron and hole states when the space charge potential flattens. This behaviour is in good agreement with recent selfconsistent calculations. In Fig. 2a the selfconsistent potential is shown for two different excitation levels of sample # 2432 with the design parameters given in Fig. 2b. These results exemplify the strong dependence of the effective gap on the steady-state carrier concentration. Note that even at low photoexcitation intensity the steady-state carrier concentration in GaAs doping superlattices is already unusually high (of the order of the doping concentration) because of the small electron-hole recombination probabilities.

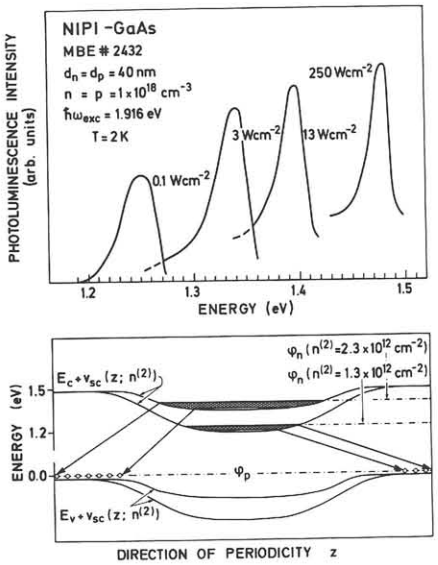

Fig. 2 (a) One period of calculated valence and conduction band edges and occupied electronic subbands (shaded areas) for two different excess carrier concentrations. For clarity, the recombination across the indirect gap is indicated to one side only. (b) Observed normalized luminescence as function of energy for various excitation densities.

Our electro- and photoluminescence studies have shown that the photon energies of radiative recombination between thermalized electrons and holes directly reflect the effective energy gap of GaAs doping superlattices which depends strongly on the concentration of injected carriers. We could confirm the tunability of the indirect energy gap in real space and thereby the tunability of luminescence for a number of samples with different design parameters. In addition, we observed a strongly enhanced red shift of the luminescence with increasing doping concentration of the constituent layers. This implies that strong tunability and high luminescence intensity far below the gap of unmodulated bulk GaAs can be achieved by only moderate variation of the photoexcitation intensity or injection current density. In particular, the tunability of electroluminescence and its high quantum efficiency makes feasible the fabrication of tunable infrared injection lasers from GaAs operating in the favorable region beyong 1.2 μm.