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HIGH QUALITY SELECTIVE CONTACTS TO *n-i-p-i* DOPING SUPERLATTICES

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Using a shadow-mask MBE technique for the fabrication of *n-i-p-i* doping superlattices with in situ grown-in selective *n-* and *p-* type contacts we have made a break-through with respect to the technical problem of selectively contacting the *n-* and *p-* layers in highly doped *n-i-p-i* superlattices. We report a number of investigations which could be performed successfully for the first time due to our new technique. Tunable room temperature electroluminescence with an external quantum efficiency of about 2 % was observed over a photon energy range corresponding to the half band gap of GaAs. In electroabsorption experiments the modulation of optical transmission through a *n-i-p-i* crystal was observed for the first time. In a *n-i-p-i* of only 2 μ m thickness a 22 % transmission change close to the bulk band gap was found. At photon wave lengths of about 1 μ m the absorption coefficient could be changed by 2 1/2 orders of magnitude by applying bias between -1.5 and +0.5 volts.

1. Introduction Doping superlattices (*n-i-p-i* crystals¹) obtained by periodic modulation of *n-* and *p-* doping during the growth of an otherwise uniform semiconductor (possibly with undoped (*i-*) layers in between), have been investigated intensively during the past years². Due to an "indirect band gap in real space" electrons and holes are spatially separated from each other. This results in interesting new properties such as extremely long electron hole recombination lifetimes, tunable electron and hole conductivity, giant photoconductivity response, tunable absorption, tunable luminescence, and tunable optical gain².

One of the unique features of *n-i-p-i* crystals is the possibility to apply "selective contacts"² to the *n-* and the *p-* layers which allows one to control the quasi-Fermi levels ϕ_n and ϕ_p in the sample by an external bias. Electron and hole injection or extraction takes place until the quasi-Fermi level difference in the sample corresponds to the external potential eU_{np} applied between such selective contacts, i.e., $\Delta\phi_{np} = \phi_n - \phi_p = eU_{np}$. The method of making selective contacts which was used in the past^{3,4} consisted in an alloying process of Sn and Zn as dopants to form continuous *n-* and *p-* type contact region by locally overcompensating the grown-in doping of opposite sign. The

problem with this kind of contacts is the deterioration of the crystal quality introduced by the alloying process in the contact region. Therefore, significant leakage currents result at these contacts in the case of *n-i-p-i* samples with doping levels above 10^{17} cm^{-3} , in particular at room temperature. In fact, the lack of satisfactory selective contacts at higher doping levels has strongly hampered, in many cases even made impossible, the observation of interesting phenomena or the realization of many device applications, as doping levels in the range of 10^{18} cm^{-3} and 10^{19} cm^{-3} are often required.

An elegant way to overcome these problems is the in situ generation of selective *n-* and *p-* type contacts by appropriate lateral structuring of the dopant concentration within the planes of the doping superlattice. Dopant ion beam writing, as proposed previously by one of us⁵, represents a particularly flexible and powerful version of this general concept, but requires sophisticated additions to a MBE chamber for its realization. In contrast, the shadow mask technique, also proposed in Ref.⁵, can be implemented very easily and still allows for a wide range of contact geometries. In the following we report on the first realization⁶ of this very simple concept.

2. Shadow masks for grown-in selective contacts The concept is shown in Fig. 1a. A silicon contact mask of a few hundred micrometer thickness on a GaAs substrate is used during MBE growth. The orientation of the stripe-shaped windows in the mask is chosen such that the Ga and the As beams are incident in the plane normal to the substrate and parallel to the stripes, whereas the Si and Be dopant beams are impinging under angles of about $\pm 30^\circ$. In this way, regular *n-i-p-i* structures are grown in the center of the window area. Towards the edges of the window, the structures change gradually (depending on the shadow width) into "*n-i-n-i*" - and "*p-i-p-i*" -type structures. These *n-i-n-i* and *p-i-p-i* regions now represent the selective contacts. The metallic contact to those can be made without any problems by the standard methods (Fig. 1b). In these structures, the only leakage currents are now due to interlayer generation or recombination processes which are strongest in the *n-i-p-i* "bulk" region and which decrease towards the contact regions. Due to the high quality of MBE-grown *p-n* junctions these leakage currents are, in fact, low. At room temperature, the current voltage characteristics of a 10.5 period *n-i-p-i* sample with $n_D \sim n_A \sim 10^{18} \text{ cm}^{-3}$ showed excellent rectifying behavior with reverse saturation current of about 200 pA at -7V for 1.2-mm-long stripe contacts and a 0.7-mm-wide *n-i-p-i* region⁶.

3. Tunable Electroluminescence In order to observe luminescence with a strong red shift and significant intensity *n-i-p-i* structures of short superlattice period and with high doping level are the most suitable ones. This design combines strong reduction of the effective bandgap and relatively large dipole matrix elements for tunneling transitions between electron and hole subband states near the respective band edges². Previously, electroluminescence in highly doped samples ($n_A = n_D = 4 \times 10^{18} \text{ cm}^{-3}$) had been only reported for excitation at liquid helium temperature^{7,8}. We have now observed room temperature electroluminescence in GaAs *n-i-p-i* samples with even higher doping ($n_A = 10^{19} \text{ cm}^{-3}$, $n_D = 4 \times 10^{18} \text{ cm}^{-3}$) which was tunable down to a peak position of the spectra below 0.8eV, i.e. over about $\frac{1}{2}$ the GaAs band gap (Fig. 2)⁹. Moreover, the quantum efficiency turned out to be quite high. The external peak efficiency of about 2%, equal to that one of commercial double hetero AlGaAs-GaAs LED's of intermediate efficiency, is reached at a luminescence peak position of 1.2eV, where the sample emits 0.1 W cm^{-2} drops only by a factor of 4 if the PL peak shifts to 0.9eV.

4. Tunable Absorption The absorption coefficient of *n-i-p-i* doping superlattices is strongly tunable for photon energies smaller than the band gap of the unmodulated host material E_g^0 , in particular if the built-in space charge fields are strong due to high doping levels^{10,11}. Also this phenomenon could now be observed at room temperature for the first time¹². Two kinds of experiments were performed. In transmission measurements the relative intensity change of the transmitted light $[I^{\pm}(\omega, U_{np}^1) - I^{\pm}(\omega, U_{np}^2)] / I^{\pm}(\omega, U_{np}^1)$ was recorded as a function of wavelength of the incident light $\lambda = 2\pi c / \omega$ for different bias U_{np} applied between the selective *n*- and *p*- contacts (Fig. 3). The maximum absolute change of transmission at $h\omega = 1.40\text{eV}$ through a $2.2\mu\text{m}$ thick *n-i-p-i* structure corresponds to a change of the absorption coefficient by $\Delta\alpha = -\ln 0.78 / 2.2\mu\text{m} = 1.1 \times 10^3 \text{ cm}^{-1}$!

Much larger relative changes of $\alpha(\omega, U_{np})$ were observed at longer wavelength in photoconductive response measurements. In these measurements the ratio of photocurrent I_{nn} between two *n*-type contacts and the incident light intensity, which is proportional to the absorption coefficient was recorded as a function of wavelength, with the bias U_{np} as a parameter (Fig. 4). At $\lambda = 1.05\mu\text{m}$ a change of α by a factor of about 200 was observed. This implies the possibility to vary the transmission through a 1mm long waveguide structure between $I^{\pm}(\lambda = 1.05\mu\text{m}, U_{np} = 0.4\text{V}) = 0.9I_0$ and $I^{\pm}(\lambda = 1.05\mu\text{m}; U_{np} = 1.5\text{V}) = 7 \times 10^{-10} I_0$. This would correspond to a modulator with low losses and high extinction ratio.

5. Conclusions We have demonstrated by our electroluminescence and electroabsorption studies that the method of shadow-mask MBE growth is suitable to overcome the problem of making selective contacts to *n-i-p-i* structures of higher doping levels. The *n-i-n-i* *n-i-p-i* *p-i-p-i* structures grown with a mask with simple stripe-shaped windows as described allows a wide variety of contact geometries. A pair of *n*- and *p*- contacts can be directly applied to long stripes for waveguide, edge emission or laser structures. Split *n-n* and *p-p* contacts, deposited onto appropriately etched mesas allow independent measurements of the *n*-layer and *p*-layer conductivities σ_{nn} and σ_{pp} as a function of the carrier concentration which can be modulated by the bias σ_{nn} and σ_{pp} applied between *n*- and *p*- contacts² (see also inset in Fig. 4). Beyond this simple scheme there are many possibilities to obtain all kinds of contact arrangements and lateral doping profiles by using different mask patterns and source arrangements in the MBE chamber, including also lateral modulation of composition in multiple quantum well structures and hetero *n-i-p-i*'s¹³.

References

1. G.H. Döhler, Phys. Status Solidi B52, 79, 533 (1972); J. Vac. Sci. Technol. 16, 851 (1979)
2. For recent reviews see G.H. Döhler, CRC Critical Reviews in Solid State and Material Sciences, Vol. 13, Issue 2, 97 (1987) or IEEE QE-22, 1682 (1986)
3. H. Künzel, G.H. Döhler, A. Fischer, and K. Ploog, Appl. Phys. Lett. 38, 171 (1981)
4. G.H. Döhler, C.J. Scott, G. Trott, and J.N. Miller (unpublished)
5. G.H. Döhler, in: The Technology and Physics of Molecular Beam Epitaxy, E.H.C. Parker, Ed. (Plenum, N.Y., 1985) p. 273
6. G.H. Döhler, G. Hasnain, and J.N. Miller, Appl. Phys. Lett. 49, 704 (1986)
7. H. Künzel, G.H. Döhler, and K. Ploog, J. Appl. Phys. Lett. 41, 852 (1982)
8. G. Abstreiter, *Two-dimensional Systems Heterostructures and Superlattices*, Proceedings of the International Winter School, Mauterndorf, (Springer, Berlin, 1984) p.232

9. G. Hasnain, G.H. Döhler, J.R. Whinnery, J.N. Miller, and A. Dienes, Appl. Phys. Lett. 49, 1359 (1986)
10. G.H. Döhler, H. Künzel, and K. Ploog, Phys. Rev. B25, 2616 (1982)
11. G.H. Döhler and P. Ruden, Phys. Rev. B30, 5932 (1984)
12. C. Chang-Hasnain, G. Hasnain, N.M. Johnson, G.H. Döhler, J.N. Miller, J.R. Whinnery, and A. Dienes, Appl. Phys. Lett. 50 (14), 915 (1987)
13. G.H. Döhler, J.N. Miller, and G. Hasnain, US Patent (filed)

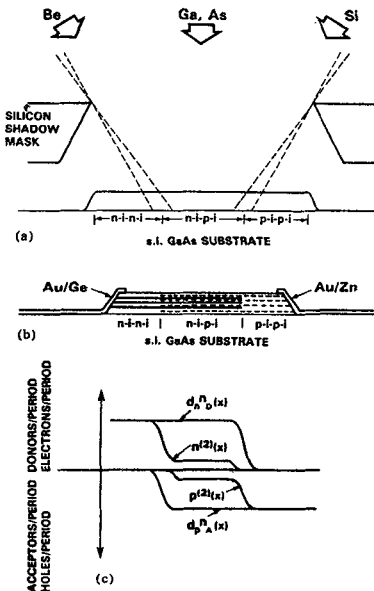
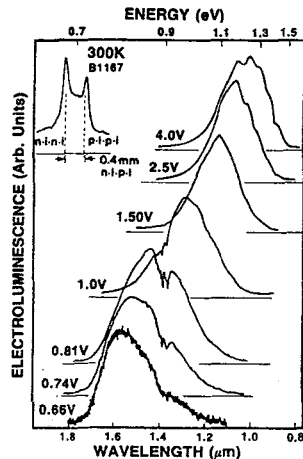


Figure 1. (a) Schematic showing MBE growth of GaAs through a shadow mask with *n*- and *p*- dopants shadowed symmetrically. (b) Cross section of the doping superlattice grown with built-in interdigitated contacts showing *n-i-n-i*, *n-i-p-i*, and *p-i-p-i* regions. (c) Lateral variation of donor, acceptor, and two-dimensional electron and hole concentration per superstructure period for a "*n-i-p-i*" semimetal.

Fig. 2. Electroluminescence spectra at 300 K of GaAs *n-i-p-i* B1167 ($n_D = 4 \times 10^{18} \text{ cm}^{-3}$; $n_A = 10^{19} \text{ cm}^{-3}$; $d_n = 25 \text{ nm}$; $d_p = 35 \text{ nm}$; 10.5 periods) for different applied bias voltages. The inset shows the near-field intensity of the EL emitted from the top of the *n-i-p-i* at $\lambda = 1.0 \mu\text{m}$ and at 4.0V bias; the two dotted lines indicate the calculated geometrical boundaries of the *n-i-n-i*, *n-i-p-i*, and *p-i-p-i* regions which are 0.4mm apart.



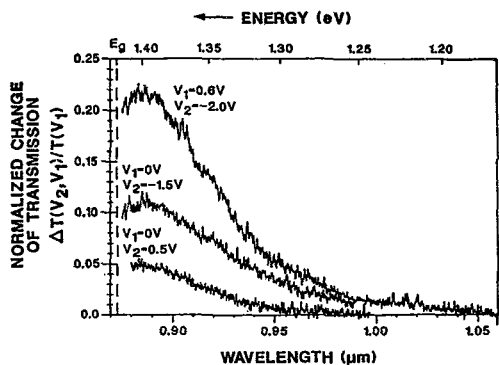


Fig. 3. Normalized change of transmission $\Delta T(V_{np^2}, V_{np^1})/T(V_{np^1})$ as a function of photon wavelength for various p - n bias voltages V_{np^1} and V_{np^2} .

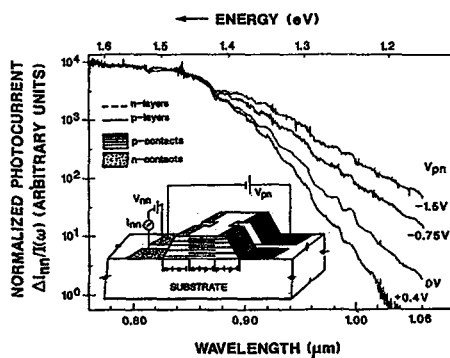


Fig. 4. The normalized photocurrent $\Delta I_{np}/I(\omega)$ as a function of photon wavelength. It approximately equals to $\alpha(\omega)$ in units of cm^{-1} .