A — 1 — 4 (Invited) n-i-p-i Superlattices - Novel Semiconductors with Tunable Properties

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In this paper we discuss electrical and optical properties and possible electrical, optical and electrooptical device applications of a new type of artificial superlattice which consists of ultrathin n- and p-doped layers, possibly separated by intrinsic layers of the same semiconducting material ("n-i-p-i crystals").[1,2]

Compared with the well-known compositional superlattices[3,4] (AlAs-GaAs, e.g.) these doping superlattices exhibit novel properties which result from a very efficient spatial separation between electrons and holes due to the periodic space-charge potential of the impurities ("indirect gap in real space") (See Fig. 1). This separation implies two unique properties of n-i-p-i crystals:1) The recombination lifetimes of charge carriers may be increased by many orders of magnitude over those of bulk material. Consequently, large deviations of the electron and hole concentration from thermal equilibrium are metastable under weak excitation conditions. 2) The space-charge-induced superlattice potential itself is strongly affected by a variation of the electron and hole concentration, e.g. by photoexcitation or carrier injection. The effective energy gap of a n-i-p-i crystal, as well as the carrier concentration are thus no longer fixed materials para-

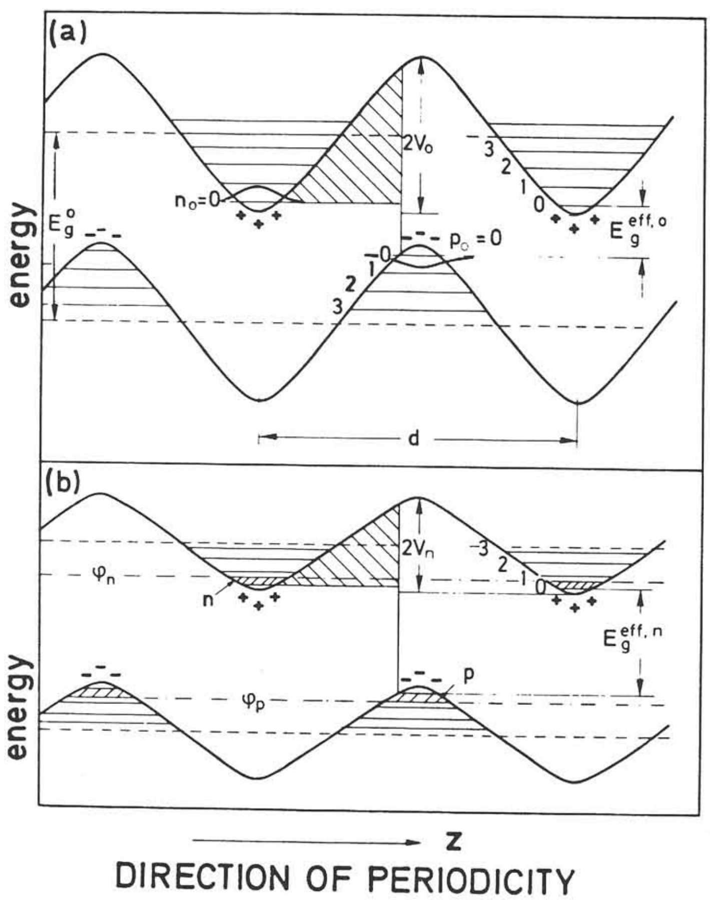

Fig. 1. Schematic real space energy diagram of a compensated nipi crystal.

a) ground state.
+ = ionized donors in the b-layers
− = ionized acceptors in the p-layers.
The concentration of mobile electrons and holes is zero. The numbers,0,1,2.. label the electron and hole subbands. The bulk energy gap E_g^o is reduced to $E_g^{eff,o}$ by the periodic space charge potential of amplitude V_o. The shaded area indicates the tunneling barrier for recombination between electrons and holes in the lowest conduction and the uppermost valence subband, respectively.

b) excited state.
A non-equilibrium situation with different quasi-Fermi levels for electrons (ϕ_n) and holes (ϕ_p) is quasi-stable due to weak recombination. Increasing electron and hole concentration n and p in the doping layers reduces the space charge and, therefore, the amplitude V_n of the periodic potential. Thus, the effective energy gap $E_g^{eff,n}$ is tuned by variation of the carrier concentration.

meters but tunable quantities. The tunability and the relation between band gap and carrier concentration opens a wide field of possible device applications of this new class of semiconductors.

Recently, GaAs doping superlattices have been grown by molecular beam epitaxy with Si as donors and Be as acceptors.[5] Among the experiments which have been performed in order to investigate the theoretically predicted pecularities the bipolar-conductivity,[6] photoconductivity,[7] absorption,[8] photo-[9,10] and electroluminescence[11] measurements are of particular interest for applications.

These experiments have confirmed that the conductivity by electrons and holes may be tuned from zero to high values with negligible leakage currents either via injection by selective electrodes[6] or by photoexcitation.[7,8] The photoconductivity experiments have also demonstrated that the absorption coefficient for photon energies below the band gap of the unmodulated semiconductor is tunable over a wide range.[8] Finally, our study of the photo- and electro- luminescence has confirmed that the luminiscence spectrum can be shifted in both cases within a range or more than 300meV below the optical gap of unmodulated GaAs, depending on excitation intensity or injection current respectively.[9-11]

The properties just mentioned provide the basis for a wide variety of new devices for the detection, modulation and generation of electrical and optical signals, including extremely sensitive photodetectors, high efficiency solar cells and very fast modulation of light absorption and emission.

<u>References</u>

1. G.H. Döhler, phys. stat. sol. (b) <u>52</u>, 79, and 533 (1972)
2. G.H. Döhler, J. Vac. Sci. Technol. <u>16</u>, 851 (1979)
3. See, for example, R. Dingle, in Festkörperprobleme: Advances in Solid State Physics, edited by H.J. Queisser (Vieweg, Braunschweig, 1975), Vol. XV, p. 21; L. Esaki and L.L. Chang, Thin Solid Films <u>36</u>, 285 (1976)
4. G.A. Sai-Halasz, Institute of Physics Conference Series <u>43</u>, 21 (1979)
5. K. Ploog, A. Fischer, G.H. Döhler, and H. Künzel, Institute of Physics Conference Series <u>56</u>, 721 (1981)
6. K. Ploog, H. Künzel, J. Knecht, A. Fischer, and G.H. Döhler, Appl. Phys. Lett. <u>38</u>, 870 (1981)
7. H. Künzel, G.H. Döhler, and K. Ploog, Appl. Phys. A <u>27</u>, 1 (1982)
8. G.H. Döhler, H. Künzel, and K. Ploog, Phys. Rev. B, <u>25</u>, 2616 (1982)
9. G.H. Döhler, H. Künzel, D. Olego, K. Ploog, P. Ruden, and H.J. Stolz, Phys. Rev. Lett. <u>47</u>, 864 (1981)
10. H.J. Stolz, H. Jung, D. Olego, H. Künzel, K. Ploog, P. Ruden, and G.H. Döhler, Solid State Commun., in press
11. H. Künzel, G.H. Döhler, and K. Ploog, to be published