Transmission spectroscopy on sawtooth-doping superlattices

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We have performed transmission experiments on sawtooth-doping superlattices of short periodicity (100–200 Å). Oscillations have been observed in the transmission spectra as a function of frequency due to the size quantization effect. We present a microscopic model of the transmission which takes into account the coupling between quantum wells in the superlattices. A Kronig-Penney model for a V-shaped quantum well is presented and the dispersion is calculated. It is found that interwell tunneling is only important for high subbands. The electron impurity scattering is included within Born approximation. The random-phase-approximation density correlation function is used for the interband absorption. Excellent agreement between theory and experiment is obtained.

I. INTRODUCTION

Doping superlattices obtained by periodic modulation of n- and p-type doping of a semiconductor during growth have been intensively studied during the past few years.[1–10] Due to the indirect energy-band gap in real space, electrons are spatially separated from holes, resulting in many interesting new properties. Generally one can differentiate between type-A and type-B sawtooth-doping superlattices.[10] Type-A samples have a short carrier lifetime ($\tau \sim 3$ ns) (Ref. 11) due to the significant overlap of the wave functions of the lowest conduction and valence subbands and have a typical period z_p of 100–200 Å. A type-B superlattice has quite different features, such as a long carrier lifetime due to the vanishing overlap of the conduction and valence subbands wave functions. The period of this type of superlattice is typically $z_p \geq 300$ Å. In a sawtooth-doping superlattice, the n- and p-type dopants are incorporated as δ-doping layers to give a sawtoothlike potential profile (Fig. 1). We recently reported studies of photocurrent spectroscopy of a type-B GaAs doping superlattice using a new selective contact method[12,13] and interpreted the measurements using a generalized Franz-Keldysh model.

In this paper, we report transmission spectroscopy measurements on type-A GaAs sawtooth superlattices. Our results show that the sample is not transparent for photon energies below the gap of the host material, due to the band modulation, and existence of low-lying intersubband transition. The wave functions in such a potential are Airy functions, and the subband levels can be obtained by imposing proper boundary conditions. The discrete subband should lead to a steplike structure in the transmission spectra (Fig. 3), and the oscillator strengths of the optical transitions can be evaluated by considering the overlap between the wave functions of the initial and final states. The level broadening is also taken into account in our formalism.

II. EXPERIMENT

The GaAs sawtooth superlattices are grown by gas-source molecular-beam epitaxy (Vacuum Generator V80 system) on a (100) oriented semi-insulating substrate. The growth temperature was kept below $T = 600\,^{\circ}\mathrm{C}$ to minimize diffusion of the n-type (Si) and p-type (Be) impurities. To reach two-dimensional (2D) doping concentrations of the order of $N_A = N_D = 10^{13}$ cm^{-2}, the Ga shutter was closed when either the Si or Be shutters were opened, and only the As shutter was open continuously. We investigated two samples, one with a nominal thickness of 0.42 μm with a nominal periodicity of 178 Å and the other with a nominal thickness 0.18 μm and a nominal periodicity of 142 Å. The thickness of the whole sample, including sheet and substrate, is 300 μm in both cases. Due to the correlation of the computer system and shutters, the periodicity z_p is 10–20 % larger than the nominal numbers.

For the transmission measurements we used a sample holder with a hole of 1 mm diameter. The experimental setup is illustrated schematically in Fig. 2. The detector was a Ge photodiode and was thermally decoupled from

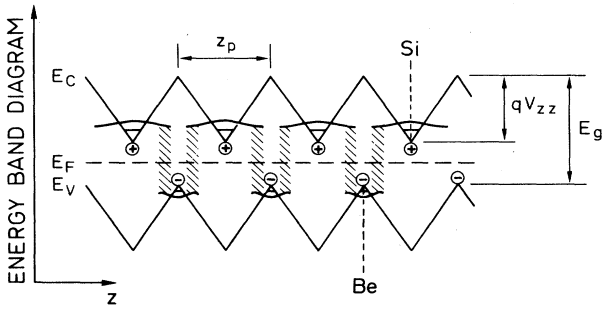

FIG. 1. Energy-band diagram of a type-A sawtooth-doping superlattice. E_g is the gap of the host material and qV_{zz} is the amplitude of the modulation of the conduction and valence band. The period of the superlattice is given by z_p. The overlap of the wave functions is indicated by shaded areas, (+) and (−) denote the position of positive and negative doping.

the sample holder. The sample transmission was measured with the lock-in technique. The chopping frequency is 313 Hz. For monochromatic illumination of the sample we used a 250-W halogen lamp with a double monochromator (HRD 600 from Jobin Yvon) incorporating 1200-lines/mm and 600-lines/mm gratings. The holographic 1200-lines/mm grating was used for most of the measurements due to the smooth optical response. This grating has cut off at 1100 nm, and to ensure that our measurements cover all transitions, we reexamined the spectra with the 600-lines/mm grating and found no further transitions in the infrared region. In addition optical filters with cut-off wavelengths of 665 and 780 nm were used.

The observed spectra are normalized to a reference measurement performed on a semi-insulating substrate with a thickness of 300 μm. In this way one can obtain transmission spectra without detailed knowledge of the response of the measuring setup. From these corrected curves we obtain the first derivative numerically. All measurements are controlled by a HP300 computer.

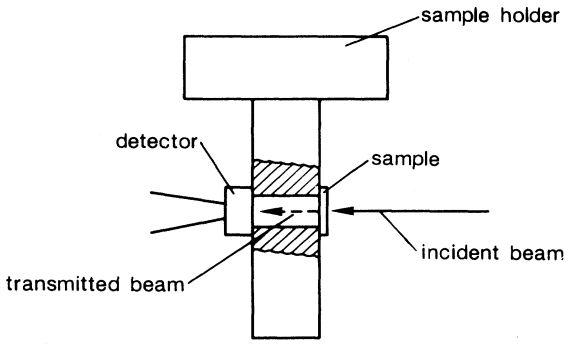

FIG. 2. Schematic illustration of the experimental arrangement.

III. ELECTRONIC STRUCTURE AND TRANSMISSION SPECTRA

The electrostatic potential in a sawtooth-doping superlattice can be written as $V(z)=2V_{zz}|z-mz_p|/z_p$ for the mth quantum well and repeat itself with periodicity z_p, where V_{zz} is the height of the well and z_p the period of the superlattice. We use the envelope function approximation to write the electronic states as

$$\psi_n^{c,v}(r,z)=e^{i\mathbf{k}\cdot\rho}\xi_n^{c,v}(z)u^{c,v}(\mathbf{p},\mathbf{r}) , \tag{1}$$

where $u^{c,v}(\mathbf{p},\mathbf{r})$ is the periodic Bloch function for the conduction or valence bands of the host material and $\xi_n^{c,v}(z)$ is the envelope function describing the quantized motion in the z direction due to the band modulation. In Eq. (1), n is the subband index and $\mathbf{k},\rho$ are 2D vectors in the x-y plane. Within the one-electron model, the wave function for the left half of the mth quantum well can be written as

$$\xi_l(z)=c_1\mathrm{Ai}(\alpha[-(z-mz_p)-\beta_n]) + c_2\mathrm{Bi}(\alpha[-(z-mz_p)-\beta_n]) , \tag{2}$$

and similarly for the right half of the well,

$$\xi_r(z)=c_3\mathrm{Ai}(\alpha[(z-mz_p)-\beta_n]) + c_4\mathrm{Bi}(\alpha[(z-mz_p)-\beta_n]) , \tag{3}$$

where $\alpha=(4meV_{zz}/z_p\hbar^2)^{1/3}$ and $\beta_n=(E_nz_p)/(2eV_{zz})$. The wave function for the next quantum well is simply differed by a phase factor $e^{ik_zz_p}$, where k_z is the superlattice momentum. The subbands energy E_n is to be determined by imposing the standard boundary condition, i.e., wave functions and its derivative continuous at each boundaries. (Unlike compositional superlattices, e.g., the $GaAs/Ga_{1-x}Al_xAs$ system, in doping superlattices, the effective mass of the electron is the same everywhere and therefore it does not affect the boundary conditions.) The dispersion relation can be obtained as[14]

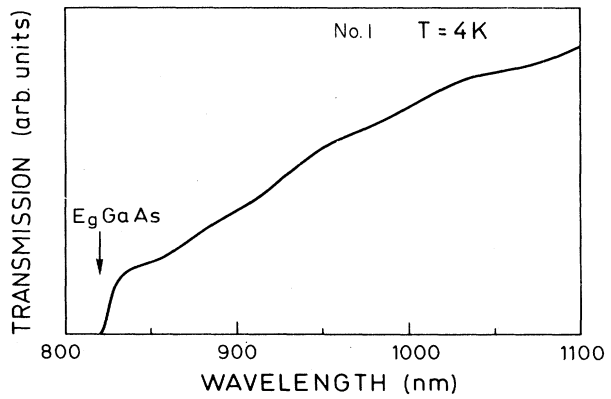

FIG. 3. Original transmission spectrum of the sample with $z_p=142$ Å and band modulation $V_{zz}=0.68$ V. The transmission vanishes for photon energy above the gap of GaAs.

$$\cos\left[\frac{k_z z_p}{2}\right]=\pi^2[(\mathrm{Ai}'\,\tilde{\mathrm{B}}\mathrm{i}'-\tilde{\mathrm{A}}\mathrm{i}'\,\mathrm{Bi}')(\tilde{\mathrm{A}}\mathrm{i}\,\mathrm{Bi}-\mathrm{Ai}\,\tilde{\mathrm{B}}\mathrm{i})+(\tilde{\mathrm{A}}\mathrm{i}'\,\mathrm{Bi}'-\mathrm{Ai}'\tilde{\mathrm{B}}\mathrm{i}')(\mathrm{Ai}\,\tilde{\mathrm{B}}\mathrm{i}'-\tilde{\mathrm{A}}\mathrm{i}'\,\mathrm{Bi})]\ , \tag{4}$$

where Ai and Bi are the Airy functions valued at $z=mz_p$ and $\tilde{\mathrm{A}}\mathrm{i}$ and $\tilde{\mathrm{B}}\mathrm{i}$ are the Airy functions valued at $z=(m+0.5)z_p$, the prime here represent the derivatives with respect to the whole argument (not to z). We have evaluated this dispersion relation for both electrons and holes. It is found that the coupling between quantum wells in the superlattice structure is negligible for lowest subbands and about several meV level broadening for first excited states of electron and light holes. The transition energy for optical transition is

$$\hbar\omega_{nn'}=E_g-gV_{zz}+E_n^c+E_{n',s}^v-\Delta E_n^c-\Delta E_{n',s}^v\ , \tag{5}$$

where E_g is the gap of GaAs and E_n is the solution of dispersion relation Eq. (4) (the subscript s standard for heavy and light holes). ΔE_n is the additional broadening due to electron-impurity or electron-phonon scattering. From the analysis of the measurements, we believe the impurity scattering is the main mechanism here. The level broadening due to the impurity scattering is

$$\Gamma_n=n_I\int\frac{d^2q}{(2\pi)^2}V_q^2\int dz\int dz'\,\xi(z)e^{-qz}\xi(z')e^{-qz'} \tag{6}$$

with $V_q=2\pi e^2/q$. From the doping profile we know that the impurity concentration inside the well is about 10^{13} cm^{-2}. The calculated level widths are decreasing functions of the increasing subband index and agree quite well with the measurements. The decreasing level width with the increasing subband index is due to the reduced electron density in the center of the wells where the impurities are located.

Now let us write down the absorption coefficient for one photon process using the Fermi golden rule[15]

$$\alpha(\omega)=\frac{4\pi e^2}{\omega c n_r m^2}\sum|\langle F|\mathbf{p}\cdot\boldsymbol{\varepsilon}|I\rangle|^2\delta(\omega-\omega_{nn'})\ , \tag{7}$$

where $\langle F|$ and $|I\rangle$ are the initial and final states, $\mathbf{p}$ is the dipole operator, c the speed of light, $\boldsymbol{\varepsilon}$ the polarization of the photon, and n_r the index of refraction. Calculation of the transmission coefficient can be performed in the standard manner. Taking into account the multiple internal reflections within the sample, we write[16]

$$T(\omega)=\frac{(1-R)^2e^{-\alpha(\omega)t}}{1-R^2e^{-2\alpha(\omega)t}}\ , \tag{8}$$

where R is the reflectivity given by $R=(n-1)^2/(n+1)^2$ in the long-wavelength limit; t is the thickness of the sample. The estimated order of magnitude of the absorption coefficient for our sample is 10^{-5}–100 cm^{-1} and so the denominator of Eq. (8) can be treated as unity. We thus have $T(\omega)=(1-R)^2e^{-\alpha(\omega)t}$ and can write its derivative with respect to wavelength as

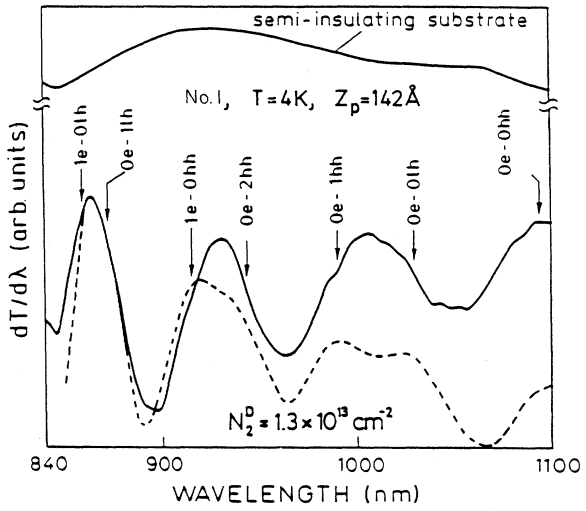

FIG. 4. First derivative of the transmission spectra measured on the samples $z_p=142$ Å measured with 1200-lines/mm grating. The behavior of the substrate is shown on the top. The arrows indicate the possible transition energies from the Airy function model. The dashed line is the calculated result.

$$\frac{dT(\omega)}{d\lambda}=\frac{tc}{\lambda^2}\frac{d\alpha(\omega)}{d\omega}(1-R)^2e^{-\alpha(\omega)t}\ . \tag{9}$$

The absorption coefficient for subband transition is a broadened step function [note the summation in Eq. (6) is over all allowed subbands] therefore its derivative has a peak when the photon energy is equal to any transition energy and has a dip when the photon energy lies in the middle of two transition energies. The calculated $dT/d\lambda$ is plotted in Fig. 4 to compare with the measurements (also see Fig. 5).

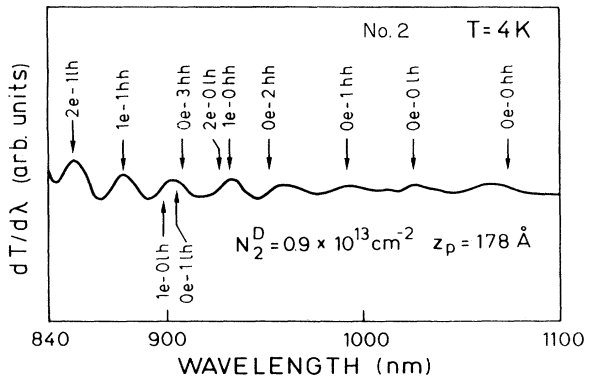

FIG. 5. First derivative of the transmission spectra measured on the samples $z_p=178$ Å measured with 1200-lines/mm grating. The arrows indicate the possible transition energies from the Airy function model.

IV. RESULTS AND DISCUSSION

In this paper we have studied both experimentally and theoretically optical transitions from the quantized subbands of doping superlattices. We have measured for the first time the interband transitions in the sawtooth superlattices. The structure due to the size quantization has been observed for several low-lying subbands at photon energies smaller than the gap of the host material. Photoluminescence spectra have also been measured in the same two samples and the transition energies obtained are consistent with the transmission measurements. Our results may shed some light on the controversial problem of dopant diffusion in doping superlattices. We found that the V-shaped potential-well model gave a very good agreement with the observed transition energies. C-V measurements on the samples grown in the same apparatus[7] also suggested that the dopants were localized within a few lattice constants. We have presented a microscopic model to calculate the subband structure and optical transitions in doping superlattices The wave function is obtained in terms of Airy functions and the energy dispersion is calculated by the Kronig-Penney model. We found that the coupling to the adjacent wells makes no significant contribution to the broadening of the low-lying subbands. However, the transmission spectra show that the low-energy transition has large widths and therefore we believe that the broadening is mainly due to scattering processes. We found that for the lower subbands the broadening due to impurity scattering is much greater than that due to the coupling between wells. However for higher subbands the interwell coupling will be stronger, while the electron density of the δ-doped layers will be reduced, the relative importance of the two broadening mechanisms is expected to change. Finally we should mention that excitonic effects are not considered in our analysis due to the following two reasons: (1) the electrons are so close to the δ-doped impurities and the electron-impurity interaction is much stronger compared to the electron-hole interaction; (2) the exciton bounding energy is much smaller compared to the level broadening. Therefore the excitonic effect is greatly suppressed by the strong electron-impurity interaction.

In conclusion, we have presented new measurements of light transmission in sawtooth superlattices. Reasonable agreement between theory and experiment is obtained.

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