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Charge depletion of n^+-$In_{0.53}Ga_{0.47}As$ potential wells by background acceptor doping

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Charge depletion from 20 monolayers of n^+-$In_{0.53}Ga_{0.47}As$, uniformly doped with Si donors and embedded within Be-doped $In_{0.53}Ga_{0.47}As$, has been studied at 1.2 K by magnetotransport measurements. Electron subband energies and densities associated with the n^+-$In_{0.53}Ga_{0.47}As$ potential well prove sensitive to the presence of the acceptors at concentrations up to $3\times10^{16}\,cm^{-3}$. Agreement between the experimental data and the electronic subband structure calculated self-consistently by solving the one-dimensional Schrödinger and Poisson equations is excellent. The results suggest that intentional background acceptor doping could be a useful mechanism for tuning subband fillings and energies in potential wells formed by highly confined donors. © *1999 American Institute of Physics.* [S0003-6951(99)00807-4]

Many electronic subbands are generally occupied in potential wells formed either by δ doping or by thin slabs doped uniformly with donors.[1,2] This is especially true in narrow gap materials,[3,4] making intersubband transitions hard to exploit for infrared detector applications.[5–8] However, this difficulty can be overcome by charge depletion of the potential well;[9] for example, asymmetric *n-i-p-i* structures can be designed with only a few electronic subbands populated.[10–13] Alternatively, a potential well can be formed by donor δ doping in an epitaxial layer with a *p*-type background, where the free electron density and subband filling depend strongly on the acceptor concentration N_A.[14–16] In this letter, electron depletion of the potential well associated with 20 monolayers (ML) of lattice matched n^+-$In_{0.53}Ga_{0.47}As$, uniformly doped with Si donors and embedded within Be-doped $In_{0.53}Ga_{0.47}As$, is reported. Subband depopulation has been studied using Shubnikov-de Haas measurements, and the electronic structure of the wells has been deduced by comparing experimental data with self-consistent calculations (SCC).

The lattice matched $In_{0.53}Ga_{0.47}As$ layers were grown by molecular beam epitaxy (MBE) at 1.0 μm/h on Fe–InP(100) substrates. The structures contained a 20-ML-thick slab, uniformly doped with approximately $3.5\times10^{12}\,cm^{-2}$ Si donors. The Si-doped slab and 30 ML of undoped InGaAs on either side of it were grown at 470 °C to minimize Si spreading by surface segregation.[2] Buffer and cap layers 0.5 μm thick were grown at 520 °C, which in the case of samples B645 and B646 were doped with 5×10^{15} and $3\times10^{16}\,cm^{-3}$ Be acceptors, respectively. A control sample (B665) was grown entirely free of Be acceptors. Shubnikov-de Haas (SdH) measurements were performed at 1.2 K in the dark on Hall bars with a 3:1 length to width ratio, in magnetic flux densities up to 13 T. The data was analyzed by fast Fourier transform techniques (FFT). The total free electron concentration n_s is the sum of the individual densities n_i over the observed subbands; $n_s=\Sigma_i n_i=\Sigma_i 2ev_i/h$, where v_i are the frequencies of the peaks in the FFT spectra, e is the electron charge, and h is Planck's constant.

The FFT spectra for B645, B646, and B665 are shown in Fig. 1, and the electron subband occupancies calculated from this experimental data are presented in Table I. The electronic subband structure was also calculated self-consistently by solving the one-dimensional Schrödinger and Poisson

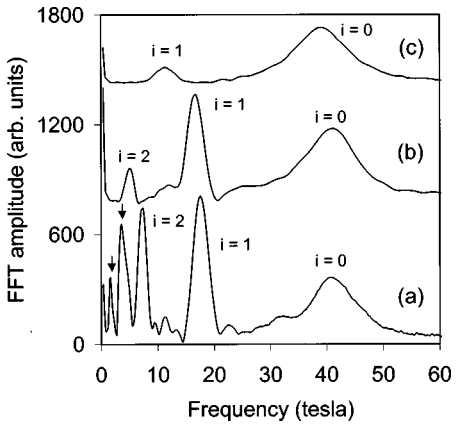

FIG. 1. Fast Fourier transform spectra for (a) sample B665 ($N_A=0$), (b) sample B645 ($N_A=5\times10^{15}\,cm^{-3}$), and (c) sample B646 ($N_A=3\times10^{16}\,cm^{-3}$). The spectra have been displaced vertically for clarity. The numbers of occupied subbands are five (B665), three (B645), and two (B646).

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TABLE I. Summary of data for InGaAs samples with (BD) and without (no BD) beryllium background acceptor doping. N_{Si}^{+} is the ionized Si concentration; Q_{depl} is the depletion charge which is required to ensure that the SCC converge (Ref. 14); n_s is the total free electron density over all subbands; n_i are the individual subband densities.

Sample	N_A ($\times 10^{16}\,\mathrm{cm}^{-3}$)	N_{Si}^{+} ($\times 10^{12}\,\mathrm{cm}^{-2}$)	Q_{depl} ($\times 10^{12}\,\mathrm{cm}^{-2}$)	n_s ($\times 10^{12}\,\mathrm{cm}^{-2}$)	n_0	n_1	n_2	n_3	n_4
					subband concentrations ($\times 10^{12}\,\mathrm{cm}^{-2}$)				
B665									
Experiment-no BD				3.37	1.96	0.84	0.35	0.16	0.06
Theory-no BD		3.4	0.001	3.37	1.956	0.842	0.384	0.151	0.038
B645									
Experiment-BD	0.5			3	1.96	0.79	0.24	⋯	⋯
Theory-BD	0.5	3.5	0.002	3	1.947	0.798	0.254	⋯	⋯
B646									
Experiment-BD	3			2.45	1.88	0.57	⋯	⋯	⋯
Theory-BD	2.8	3.6	0.06	2.41	1.851	0.562	⋯	⋯	⋯

equations.[1,9,14–16] We have shown previously[2] for samples without intentional background acceptor doping that there is close agreement between the measured and calculated values of n_i for a 20-ML-thick slab of Si–InGaAs when Si spreading is absent and the fitting parameter for the SCC (the physical extent of the Si donors, w_{Si}) is set equal to the thickness of the slab (i.e., 20 ML). This is further confirmed by comparing theory and experiment for the control sample B665 (see Table I), where five occupied subbands are observed [Fig. 1(a)] with $n_s = 3.4\times 10^{12}\,\mathrm{cm}^{-2}$. The corresponding measured values of n_i for samples B645 ($N_A = 5\times 10^{15}\,\mathrm{cm}^{-3}$) and B646 ($N_A = 3\times 10^{16}\,\mathrm{cm}^{-3}$) are also shown in Table I. For B645, $n_s = 3.0\times 10^{12}\,\mathrm{cm}^{-2}$, indicating that approximately $0.5\times 10^{12}\,\mathrm{cm}^{-2}$ or 15% of the charge has been removed from the potential well compared with B665. The two upper subbands $i=4$ and 3 have been completely depopulated, decreasing the number of occupied energy levels from five (layer B665) to three [Fig. 1(b)]. The electrons in the $i=2$ and 1 subbands have been depleted unevenly, by 21% and 6%, respectively. In contrast, the lowest energy $i=0$ subband has retained all its charge. For an increase of N_A to $3\times 10^{16}\,\mathrm{cm}^{-3}$ (B646), the total free electron density decreases to $2.45\times 10^{12}\,\mathrm{cm}^{-2}$, distributed between the two lowest subbands. Despite a decrease in the total charge by 30% compared with the corresponding value for the undepleted potential well (B665), the electron density of the lowest subband (n_0) has remained almost constant, changing from $1.96\times 10^{12}\,\mathrm{cm}^{-2}$ (B665 and B645) to $1.88\times 10^{12}\,\mathrm{cm}^{-2}$ (B646).

The calculated band structures for samples with and without intentional Be doping are shown in Fig. 2. With Be doping, the Fermi energy E_F is assumed to be pinned to the binding energy of the acceptors E_A. As N_A is increased, more and more electrons will be removed from the potential well into those acceptor states which are located closest to the Si-doped slab and which have been pushed below the Fermi energy by band bending. Regions of fixed negative space charge are thus formed on either side of the well. The resulting net excess of ionized Si donors in the well causes an increase of well depth and tighter confinement of the wave functions for the remaining free electrons. The SCC using the ionized Si donor density N_{Si}^{+}, the doping profile width w_{Si}, and the volumetric Be concentration N_A as fitting parameters predict that both the subband energies and charge depletion of the subbands increase with N_A at a progressively higher rate with increasing subband number.[14–16] Our experimental data confirm this trend [Figs. 1(b) and 1(c), and Table I]. Moreover, the occupancies of the higher energy levels are very sensitive to the magnitude of N_A due to their lower electron densities, so that only low *p*-type doping densities (i.e., $N_A \approx 10^{14}-10^{15}\,\mathrm{cm}^{-3}$) are needed to depopulate them completely. Similar behavior has been predicted by Henriques[15] and Hai and Studart[16] for Si δ-doped GaAs.

Another consequence of the tighter electron confinement

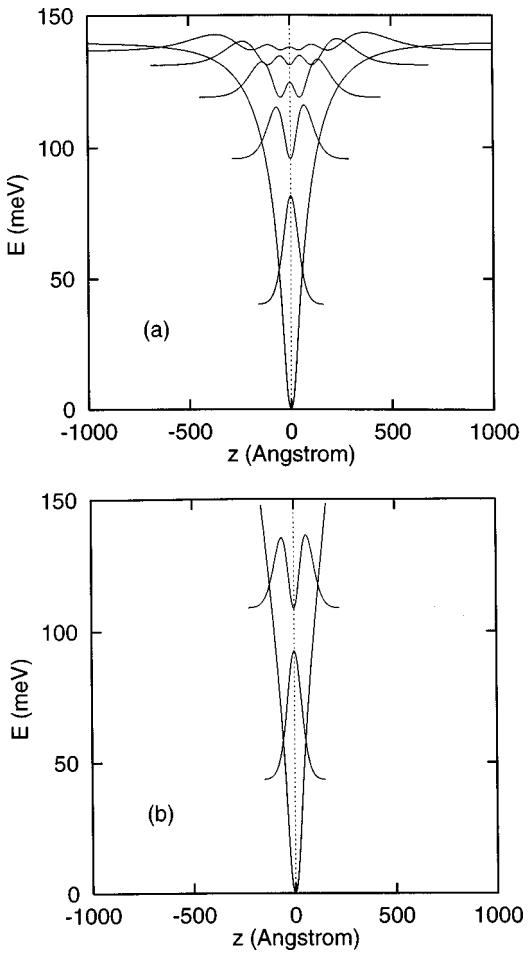

FIG. 2. Energy band diagrams for $In_{0.53}Ga_{0.47}As$ (a) with no background acceptors ($N_A = 0$) and (b) with an intentional background acceptor concentration of $2.8\times 10^{16}\,\mathrm{cm}^{-3}$. The Fermi energy is assumed to be pinned to E_A, the acceptor binding energy (140 meV from the bottom of the conduction band at the center of the well).

by background acceptor doping is a significant increase of the subband ratio $n_{i=0}/n_{i=1}$ from 2.333 for B665 (no Be acceptors) to 3.295 for B646. The latter value is also higher than that predicted for a total areal Si density of $2.45\times10^{12}\,\mathrm{cm}^{-2}$ distributed through 20 ML (2.453), and even for $2.45\times10^{12}\,\mathrm{cm}^{-2}$ Si donors confined to 2 ML (2.622), both ratios calculated with $N_A=0$. The accumulated evidence, both experimental and theoretical, suggests that the deviation of the subband densities and energies for B645 and B646 from the values for B665 is caused by the intentional introduction of acceptors. It is not a result of Si spreading because (i) all three samples were grown with the same temperature profile, and (ii) Si spreading will lead to both a reduction in the $n_{i=0}/n_{i=1}$ ratio and an increase rather than decrease in the number of occupied subbands.[2]

SCC were performed for layers B645 and B646 with $w_{\mathrm{Si}}=20\,\mathrm{ML}$ and $E_A=24\,\mathrm{meV}$. For B645, excellent agreement is achieved with $N_{\mathrm{Si}}^{+}=3.5\times10^{12}\,\mathrm{cm}^{-2}$ and $N_A=5\times10^{15}\,\mathrm{cm}^{-3}$, while for B646, the best agreement is for $N_{\mathrm{Si}}^{+}=3.6\times10^{12}\,\mathrm{cm}^{-2}$ and $N_A=2.8\times10^{16}\,\mathrm{cm}^{-3}$ (Table I). The latter value of N_A is slightly different from the intended background acceptor concentration but within error limits for doping control in MBE growth. The corresponding depletion thicknesses D_{SCC} (defined as the separation between the two points in the structure where the Fermi and acceptor energies coincide) are $1.061\pm0.1\,\mu\mathrm{m}$ for B645 and $0.438\pm0.04\,\mu\mathrm{m}$ for B646. These values are in good agreement with the depletion layer thickness $D_{\mathrm{depl}}=(\epsilon(E_G-E_A)/2\pi e^2N_A)^{1/2}$ derived from electrostatics using $E_G=0.81\,\mathrm{eV}$ and $\epsilon=13.93$, and valid when the space-charge region extends beyond the extent of the wave functions of the confined electrons; $D_{\mathrm{depl}}(\mathrm{B645})=0.984\,\mu\mathrm{m}$ and $D_{\mathrm{depl}}(\mathrm{B646})=0.416\,\mu\mathrm{m}$. Despite 30% depletion of the electron density from B665 to B646, the Fermi energy remains constant at $\approx$140 meV above the conduction band minimum, demonstrating both the increase in potential well depth and the energy spacing between the remaining occupied subbands. (For comparison the Fermi energy predicted for a free electron density of $2.45\times10^{12}\,\mathrm{cm}^{-2}$ provided by an equal number of ionized Si donors uniformly distributed in 20 ML is 110 meV.) Even higher subband energy separations are predicted for ideal Si δ doping with larger densities and background acceptor concentrations than those investigated, substantially exceeding the equivalent values for undepleted wells.

In conclusion, the electron subband energies and densities associated with 20 ML of n^{+}-$In_{0.53}Ga_{0.47}As$, uniformly doped with Si donors prove sensitive to the presence of the background acceptors at concentrations up to $3\times10^{16}\,\mathrm{cm}^{-3}$. The electron concentrations of the lower occupied subbands remain constant despite a significant decrease of the overall free electron density. Complete depletion of the well can be observed by increasing N_A. It is proposed that the procedures described here can be applied more generally where either intrinsic or extrinsic defects remote from a potential well pin the Fermi energy and thus influence the free charge energies and distributions within the well.

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