Multiquantum well structure with an average electron mobility of 4.0×10^6 cm^2/V s

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(Received 12 February 1992; accepted for publication 8 July 1992)

We report a modulation-doped multiquantum well structure which suppresses the usual ambient light effect associated with modulation doping. Ten GaAs quantum wells 300-Å wide are symmetrically modulation doped using Si δ doping at the center of 3600-Å-wide $Al_{0.1}Ga_{0.9}As$ barriers. The low field mobility of each well is 4.0×10^6 cm/V s at a density of 6.4×10^{10} cm^{-2} measured at 0.3 K either in the dark, or during, or after, exposure to light. This mobility is an order of magnitude improvement over previous work on multiwells.

We have extended our recent work on the molecular beam epitaxy (MBE) of modulation-doped inverted interfaces[1] to fabricate a multiquantum well structure with the remarkable properties of very high electron mobility, insensitivity to ambient light, and very uniform well-to-well carrier density and mobility. Issues relating to inverted interfaces (formed whenever GaAs is grown over AlGaAs are central to multiquantum well structures because one-half of the interfaces in such structures are inverted, and in general the modulation doping is across both normal and inverted interfaces.

Our practical prescription given in Ref. 1 for obtaining high mobility transport in modulation-doped inverted interfaces is to optimize the MBE growth conditions to high substrate temperatures and lean As conditions where the best normal interfaces are grown, and then to compensate for the observed tendency of the Si dopant to migrate in the growth direction, by increasing the undoped AlGaAs setback between the Si dopant and the inverted interface. In the present case, we were interested in a multiquantum well sample having many identical quantum wells each with a very low electron density. Because the modulation-doped charge transfer across an undoped setback, d, to a quantum well ΔE_c deep, is to first-order proportional to $\Delta E_c/d$, such low carrier density quantum wells conveniently correspond to large undoped setbacks along with barrier alloys of low Al content.

The structure of our low-density multiwell along with the corresponding energy profile of the conduction band edge is shown in Fig. 1. The substrate temperature during growth was at the GaAs congruent sublimation temperature (640 °C), and the As_4 beam-equivalent flux was 8×10^{-6} Torr. The Si δ doping near the center of each barrier is designed to modulation dope the quantum wells above and below equally to 3.2×10^{10} carriers/cm^2. The slight 1900 to -1700 Å asymmetry in the inverted-to-normal undoped setbacks is incorporated to compensate for the expected $\sim$100 Å drift of the Si toward the sample surface during MBE growth.[1] The 300 Å quantum-well width was chosen as a compromise to minimize both interface roughness scattering in narrow wells,[2] and intersubband mixing effects. The amount of Si dopant is chosen to be enough to pull the conduction band edge to very near the Fermi level at the location of the ionized Si^+. Because each well is symmetrically doped from above and below, and because of the low Al content in the AlGaAs barriers, and the unusually large undoped setbacks, the bottoms of the quantum wells are symmetric and unusually flat.

Figure 2 shows the conventional four-probe magnetoresistance, ρ_{xx} and ρ_{xy} of a 10-well sample of the type in Fig. 1 grown by MBE at the GaAs congruent sublimation temperature.[1] The average electron mobility in the 10 wells measures 4.0×10^6 cm^2/V s at 0.3 K. From the extremely narrow fractional quantum Hall effect (FQHE) states in the magnetoresistance, ρ_{xx}, at $\nu=2/5$ and 1/3, we conclude each of the 10 wells has the same carrier density 6.4×10^{10} cm^{-2} with an individual variance of no more than a few percent. As stated above neither the mobility nor the carrier density were affected by the presence or absence of ambient light. The well-to-well uniformity is confirmed by the ρ_{xy} spectrum, which shows the FQHE resistances to be quantized precisely at

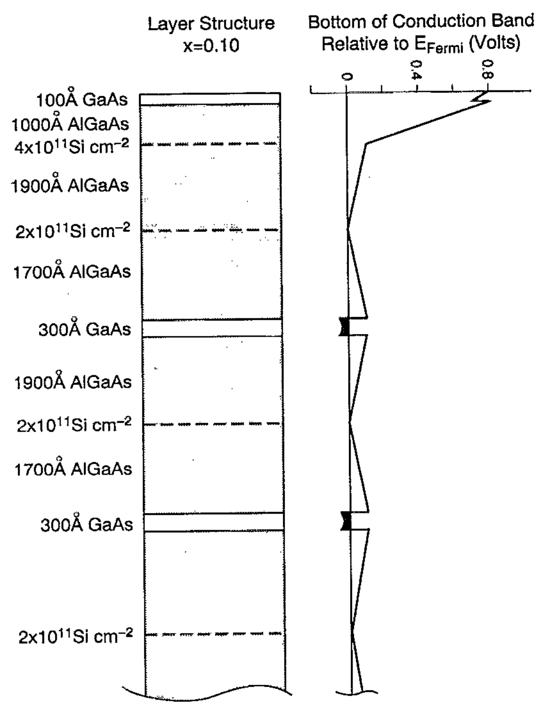

FIG. 1. Structure of the multiquantum well sample together with the corresponding conduction band edge profile.

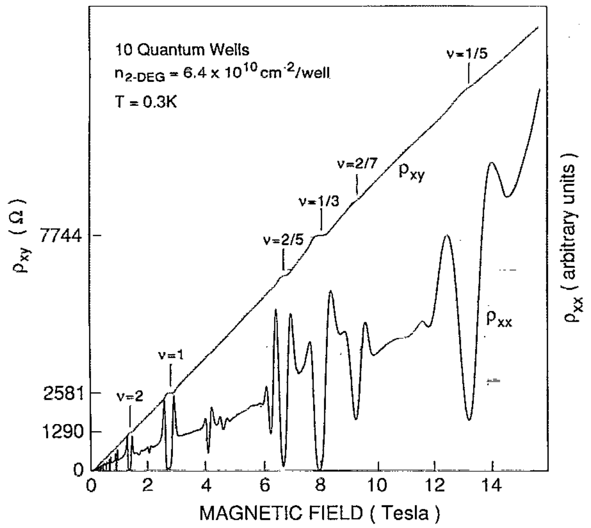

FIG. 2. Magnetotransport spectra of a 10 quantum well sample having the structure described in Fig. 1.

$$R_{xy}=\frac{1}{10}\frac{h}{\nu e^2} \tag{1}$$

as would be expected only if each of the 10 quantum wells participated equally in the transport.

We conclude with discussions on the origin of the remarkable insensitivity of the sample to light, and on possible structural reasons for its unusually high quality in magnetotransport. Modulation-doped samples are usually sensitive to exposure to ambient light by two mechanisms, both of which typically result in an increase in carrier density and mobility: (i) ionization of either DX^0 or DX^- centers to DX^+ with the promotion[3] of additional carriers to the conducting channel, and (ii) the creation of electron-hole pairs by above-band-gap light, which in some structures can be separated by internal electric fields to result in additional carriers in the channel. Mechanism (i) is strongly suppressed in our sample by the low Al content of our barrier alloy. For $Al_{0.1}Ga_{0.9}As$ the DX ground state is believed to be nearly empty as it is more than 130 meV above[3] the level of the conduction band in GaAs. Mechanism (ii) is also suppressed in our sample by the symmetric fields caused by our deliberate pinning of the conduction band edge at the Fermi level in the vicinity of the ionized Si^+ on both sides of each well (see Fig. 1). This symmetric pinning causes optically created electron-hole pairs to remain in the well where they recombine. Moreover, conduction electrons created above the AlGaAs band gap move to the Si^+ ions without augmenting the carrier population.

We referred above to the unusually high quality of the magnetotransport. Look for example at the $\nu=1/5$ FQHE state. The ρ_{xx} spectrum shows a sharp $\nu=1/5$ resonance that falls to only 20% of its value in the adjacent wings. The well-developed hierarchy emanating from the Laughlin 1/3 state (at 2/5, 3/7, and even 4/9) further attest to the unusual sample quality. Why should a multiquantum well structure, which until this work had never been reported,[4] to have a mobility above $\sim 0.5\times 10^6\ cm^2/V\,s$, show such remarkable quality? We speculate that the low Al content of the AlGaAs barriers and the symmetric doping from both sides of the well may be important. The low Al content of the barriers might be expected to reduce alloy fluctuations in the barriers, which could be especially important at the quantum well interfaces. Moreover, by having two dopant layers of Si, the carriers in each well see two fixed charge distributions at twice the undoped setback that would have been required for single side doping. In addition, because the Si dopant is supplying two wells, the fixed ionized charge density in each Si layer can be at least twice as high without inducing a parallel conduction channel. This reduces the granularity in the fixed Si^+ charge distribution by $2^{-1/2}$. Taken together, the remote ionized scattering from the fixed ionized Si charges might be reduced by the order of $2^{-3/2}$. It is also possible that the carriers in the adjacent wells are themselves providing some additional remote screening of the intervening Si^+ ions. These improvements are bought at the cost of a higher carrier density near the inverted interface, but with the large undoped setbacks used here and in Ref. 1, the advantage appears to go with quantum wells that are modulation doped from both sides.

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[2] H. Sakaki, T. Noda, K. Hirakawa, M. Tanaka, and T. Matsusue, Appl. Phys. Lett. **51**, 1934 (1987).
[3] For a review of *DX* centers see, for example, P. M. Mooney, Semicond. Sci. Technol. **6**, B1–B8 (1991).
[4] See, for example, J. H. English, A. C. Gossard, H. L. Stormer, and K. W. Baldwin, Appl. Phys. Lett. **50**, 1826 (1987).