I. INTRODUCTION

The intrinsically high mobility of electrons in narrow-gap semiconductors makes InSb thin films attractive for magnetic-field sensing applications. At present, Te-doped InSb epilayers are paired with rare-earth metal magnets in automotive position-sensing applications where accuracy and repeatability are critical.\(^1\) These devices exploit a geometrical magnetoresistance where sensitivity is proportional to mobility squared.\(^2\) The 1.5 \(\mu\)m thick InSb layers are grown on GaAs substrates and have an electron concentration of 8 \(\times 10^{16}\) cm\(^{-3}\) and a mobility of \(\mu = 40\ 000\) cm\(^2\)/V s. The layers must be doped in order to reduce the temperature dependence of the electron concentration and, in turn, the temperature dependence of the sensor output. Unfortunately, the accompanying increase in ionized impurity scattering reduces the electron mobility and, consequently, the device sensitivity.

Remotely doped InSb quantum-well structures\(^3\) are potentially better suited for magnetoresistance applications than uniformly doped InSb epilayers. Increased sensitivity is possible since a high mobility can be maintained while achieving a high extrinsic electron concentration. Also, the temperature dependence of the electron concentration can be reduced since only two thin layers of InSb are required. In this article, we report on the electrical properties of InSb multiple-quantum-well structures grown by molecular beam epitaxy (MBE) on GaAs(001) substrates. Mobilities up to 41 000 cm\(^2\)/V s at room temperature and 209 000 cm\(^2\)/V s at 77 K are observed in Hall-effect measurements. Although the room-temperature mobility is the same as in the uniformly doped InSb mentioned above, the electron concentration in the quantum wells, 2.4 \(\times 10^{17}\) cm\(^{-3}\), is several times larger. Morphological characterization by atomic force microscopy indicates that roughness at the well/barrier interfaces may be a factor limiting the electron mobility. Increases in both the mobility and the electron concentration are anticipated from modifications to the layer structure.

II. EXPERIMENT

All InSb/Al\(_{1-x}\)In\(_x\)Sb growths were performed in an Intevac Modular Gen II molecular beam epitaxy system. Effusion cells were loaded with In (7N RASA), Al (6N Ulvac, Sb (6.5N Dowa), and Si (Silicon Sense). An EPI Sb cracker was used with a cracking zone temperature of 900 °C. Growth rates for InSb and AlSb were calibrated and Al\(_{1-x}\)In\(_x\)Sb composition was deduced from temporal oscillations in the intensity of the reflection high-energy electron diffraction (RHEED) pattern and verified through high-resolution x-ray diffraction. An Al\(_{1-x}\)In\(_x\)Sb alloy composition with \(x = 0.09\) was maintained to keep the lattice mismatch to InSb below \(-0.5\)% while allowing for a sufficiently large barrier for the electrons in the quantum wells.\(^4\) The Sb-to-group-III flux ratio was slightly larger than unity with an InSb growth rate of \(\sim 0.8\) ML/s. Delta doping was performed under an Sb flux and at a Sb cell temperature of 1273 °C \([\sim 5.3\times 10^{11}\) net donor atoms cm\(^{-2}\) s\(^{-1}\)]. Substrate temperatures were calibrated through changes in the static (Sb flux only) RHEED pattern upon crossing the transition temperature \(T_e = 390\) °C, at which the Al\(_{1-x}\)In\(_x\)Sb surface reconstruction changes between \(c(4\times4)\) and pseudo-\((1\times3)\).

The layer structure describing all the samples studied is shown in Fig. 1.\(^6\) Growth was carried out on semi-insulating GaAs(001) substrates in order to eliminate electrical conduction through the substrate. Since the lattice constant of GaAs is \(-14\)% smaller than that of InSb and Al\(_{1-x}\)In\(_x\)Sb, a 1 \(\mu\)m buffer layer of AlSb, which has an intermediate lattice constant, was grown directly on the GaAs substrate.\(^7\) A 1 \(\mu\)m thick Al\(_{1-x}\)In\(_x\)Sb layer was grown next, then followed by a ten-period 25-Å-Al\(_{1-x}\)In\(_x\)Sb/25-Å-InSb strained-layer superlattice for dislocation filtering and surface smoothing. A 3 \(\mu\)m Al\(_{1-x}\)In\(_x\)Sb buffer layer was grown to promote full lattice relaxation as well as to isolate the carriers from scattering centers associated with this relaxation. The Al\(_{1-x}\)In\(_x\)Sb buffer layer was grown at \(T_e + 50\pm 5\) °C, since growth on a pseudo-\((1\times3)\), as opposed to \(c(4\times4)\), surface reconstruction results in better pseudomorphic growth.

Electrons are supplied to each strained InSb quantum well

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\(^{a}\)Electronic mail: kjgoldam@mail.nhn.ou.edu

\(^{b}\)Current address: Quantum Epitaxial Designs, Inc., 119 Technology Drive, Bethlehem, PA 18015.
by Si δ-doped layers ($\sim 5 \times 10^{11}$ cm$^{-2}$ net donor density) in adjacent Al$_{x}$In$_{1-x}$Sb barriers. Each of the $N$ quantum wells is 220 Å thick, which is below the Matthews and Blakeslee critical thickness.$^8$ All layers following and including the last 0.1 μm of the Al$_{x}$In$_{1-x}$Sb buffer layer were grown at a substrate temperature of $T_r = 305 \pm 5$ °C in order to minimize Si compensation.$^9$ Additional Si atoms were included in the δ-doped layer nearest to the surface in order to provide $\sim 2 \times 10^{12}$ cm$^{-2}$ electrons for surface states. An InSb cap was added to prevent possible oxidation of an Al$_{x}$In$_{1-x}$Sb surface.

Hall-effect measurements at magnetic fields up to 0.25 T were performed on square samples whose edges are ~4 mm long. Electrical contact was made at each corner of a sample by alloying In at ~230 °C in a H$_2$ (20%) /N$_2$ (80%) atmosphere for 5 min. Ohmic contact was checked through observation of linear current–voltage characteristics. Resistivity was determined from van der Pauw measurements at 300 and 77 K.$^{10}$

After growth was completed, samples were scanned in air using a Topometrix atomic force microscope running in non-contact phase mode. The high-resonant-frequency silicon tip had an aspect ratio of approximately 3:1 and a radius of curvature less than 200 Å.

III. RESULTS AND DISCUSSION

A. Spacer dependence in single-quantum wells

A series of six single-quantum-well structures ($N=1$) was grown with Al$_{x}$In$_{1-x}$Sb barrier layers sandwiching a 220 Å thick InSb quantum well. To provide electrons for the quantum well and surface states, a single Si δ-doped layer was placed in the upper Al$_{x}$In$_{1-x}$Sb barrier a distance 100 Å $\leq d \leq 500$ Å above the InSb quantum well. Figure 2 shows the measured electron density $n$ and mobility $\mu$ of the samples at 77 K.

A simple electrostatic model can be used to explain the observed dependence of electron density on spacer layer thickness:

$$\frac{q n}{\varepsilon} = \frac{E_b - E_F}{q d},$$

(1)

$$n = \int_{E_0}^{E_F} \frac{m_{edge}^*}{\pi \hbar^2} \left(1 + \frac{2E}{E_g}\right) dE.$$  

(2)

Equation (1) describes the electric field in the spacer layer if background ionized impurities are ignored and the Fermi level at the δ-doped layer is pinned at the conduction-band edge. The well density at zero temperature is calculated in Eq. (2), assuming only a single subband is occupied and using the density of states determined from the two-band model. Values of $E_g = 200$ meV for the band gap, $m_{edge}^* = 0.0145m_0$ for the band-edge mass, and $\varepsilon = 17.7\varepsilon_0$ for the dielectric constant are appropriate for InSb. The barrier height $E_b = 142$ meV was deduced by assuming that 85% of
the InSb/Al$_{1-x}$Sb band-edge discontinuity appears in the conduction band. In calculating the subband energy $E_0 = 24$ meV, strain and the nonparabolic dispersion relation were taken into account but the effects of band bending were ignored. Equations (1) and (2) can be combined to express $n$ as a function of $d$. The results of this calculation are shown as a solid line in Fig. 2(a). Although in good agreement with the data, uncertainties in $E_F$ at the $\delta$-doped layer, $E_B$ (due to the unknown value of the conduction-band offset), and $E_0$ (due to neglecting band bending) may still be important.

The dependence of $\mu$ and $d$ [Fig. 2(b)] reveals the strong effect of remote ionized dopant scattering. Since $n$ is much less than the net donor density provided by the single $\delta$-doped layer, the majority of donor electrons must reside in surface states. As will be shown below, an improvement in mobility was observed in multiple-quantum wells where most of the electrons in the wells are far from the heavily doped layer near the surface.

B. Dependence on number of quantum wells

A series of multiple-quantum-well structures ($1 \leq N \leq 14$) was grown in which the only parameter intentionally varied was the number of quantum wells. The distance from each dopant layer to the nearest quantum well was $d = 600$ Å. The room-temperature and 77 K values for $n$ and $\mu$ are shown in Fig. 3. The dependencies on $N$ result from the increasing importance of conduction through the quantum wells with increasing $N$.

The filled circles in Fig. 3(a) show that $n$ at 77 K is linearly proportional to the number of filled quantum wells. When a quantum well is remotely doped on both sides, the left-hand side of Eq. (1) must be divided by 2. Consequently, the electron density in the well closest to the substrate will be as predicted in Fig. 2, while the other $N - 1$ wells will have densities that are 1.7 times greater. Therefore, the number of filled quantum wells is defined as $N - 0.4$. As in the previous section, we make the approximation that $n$ at 77 K is due entirely to extrinsic electrons $N \times e_{well}$ that reside in the quantum wells but originate from Si dopants in the barrier layers. Hence, a value for $e_{well}$ can be deduced from a line of best fit that also passes through the origin. The slope of such a line, shown in Fig. 3(a), gives $e_{well} = 3.5 \times 10^{11}$ cm$^{-2}$.

The density at room temperature is the sum of $N \times e_{well}$ plus the intrinsic densities in the quantum wells $N \times i_{well}$, the barrier layers $N \times i_{bar}$, and the buffer layers $i_{buffer}$. From the slope of a line fit to the room-temperature points and forced through $i_{buffer}$ at the ordinate axis, a value of $e_{well} + i_{well} + i_{bar} = 4.5 \times 10^{11}$ cm$^{-2}$ is determined. A value for $i_{buffer}$ of $2.6 \times 10^{11}$ cm$^{-2}$ is determined from a Hall measurement on a structure with the quantum wells and barriers etched off. Since the band gap of AlSb is very large, $i_{buffer}$ is assumed to be due entirely to electrons in the 4 μm Al$_{1-x}$In$_x$Sb layer. Multiplying $i_{buffer}$ by a ratio of thicknesses (1200 Å/4 μm) yields an estimate of $i_{bar} = 0.8 \times 10^{10}$ cm$^{-2}$. A value for $i_{well} = 4.5 \times 10^{11}$ cm$^{-2}$ is then the density in the quantum wells that can then be deduced. Dividing $i_{well}$ by the well thickness of 220 Å yields a concentration of $4.2 \times 10^{16}$ cm$^{-2}$, a value comparable to that measured in intrinsic InSb layers ($\sim 2 \times 10^{16}$ cm$^{-2}$). The consistency of the deduced values of $i_{buffer}$, $i_{bar}$, and $i_{well}$ with measured values of Al$_{1-x}$In$_x$Sb and InSb layers is evidence for the validity of our model.
The density values deduced above can be used to model the $N$ dependence of the room-temperature mobility. As shown in Fig. 3(b), a trend toward higher mobility is evident with increasing $N$. As discussed above, an appreciable density of intrinsic carriers is present in the Al$_{1-x}$In$_x$Sb buffer and barrier layers at room temperature. As a result, the room-temperature transport behavior is expected to be a combination of both intrinsic electrons in the buffer, barrier, and wells, and extrinsic electrons in the wells. For the structure with $N=1$, the percentage of electrons that are extrinsic is $\sim 53\%$, the ratio between $n$ at 77 K and $n$ at room temperature. This percentage can be increased by growing structures with more periods. Each additional period adds a 220 Å thick structure. This percentage can be increased by growing structures with more periods. Each additional period adds a 220 Å thick structure. The very high density of the alloy layers, and consequently the measured density values in this equation were determined as dis-...
IV. CONCLUSIONS

In InSb quantum wells with Al$_{x}$In$_{1-x}$Sb barrier layers δ-doped with Si, room-temperature electron mobilities as high as 41 000 cm$^2$/V s were observed for electron concentrations of $2.4 \times 10^{17}$ cm$^{-3}$. Even higher mobility should be possible with improved surface morphology and higher electron concentrations should result from decreasing the quantum-well-to-dopant distance.

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6The layer sequence of the $N=1$ structure with $d=600$ Å is not described by Fig. 1. A second δ-doped layer (10 s) was added 600 Å below the quantum well.