Quantum well GaAs/AlGaAs shallow-donor far-infrared photoconductors grown by molecular-beam epitaxy

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Photoconductors utilizing planar-doped silicon shallow donors in GaAs quantum wells formed with AlGaAs barriers have been fabricated and measured to have far-infrared (FIR) resonant-wavelength responsivities of ~ 1 V W^{-1}, with noise equivalent power values of $\sim 1\times10^{-7}$ W Hz$^{-1/2}$ at 4 K. The technology makes possible the use of FIR photoconductive magnetospectroscopy to measure the well position of sheet-doped silicon ions when incorporated at doping levels below 1×10^{16} cm^{-3}. A comparison of the measured position of the ions with the intended position reveals a discrepancy that can be linked to the growth parameters used to produce the structure.

I. INTRODUCTION

In 1985, Jarosik *et al.*[1] reported far-infrared (FIR) spectra from donors placed in GaAs quantum wells (QWs). By measuring the small decrease in sample transmission that occurs when an incident photon matches the energy of an allowed donor transition, they were able to study the magnetic field dependence of the observed spectral lines. Their work opened a new area of study, shallow donors in quasi-two-dimensional systems, and motivated research both in understanding the underlying physics and in developing better measurement schemes.

Typically, the change in the power of the transmitted beam is only 1% or 2%, because the transition energy of the donors is a function of well position and the number of donors per unit volume is very low. This results in spectra with low signal-to-noise ratios. Over the past few years, we[2,3] and others[4,5] have fabricated QW shallow-donor structures into photoconductors and measured their spectral response at 4 K with FIR magnetospectroscopy. This technique, which is analogous to that already proven extremely valuable in bulk film studies, produces spectra with high signal-to-noise ratios.

In this article, we present details of the growth and fabrication of our photoconductors and demonstrate how FIR photoconductive magnetospectroscopy can be used to measure the well position of sheet-doped silicon ions at doping levels below 1×10^{16} cm^{-3}. A comparison of the measured position of the ions with the intended position is given, along with relevant growth parameters.

II. EXPERIMENTAL PROCEDURE

The conduction band diagrams along with intended sheet doping positions for the three samples used in this work (labeled A, B, and C) are shown in Fig. 1. All were grown in a 2 in. elemental-source molecular-beam epitaxy (MBE) machine at 680 °C, with an intended ~ 50 nm thickness of the GaAs QWs and an intended 15%–20% AlAs concentration in the AlGaAs barriers. Arsenic overpressure growth interruptions lasting 5 s were used between the well and barrier layers in order to improve interface morphology. As shown in the figure, sample A comprised 25 QWs, sample B comprised 200 QWs, and sample C comprised 175 QWs, with all wells ~ 50 nm wide. For sample A, the center 10 nm wide portion of each well, and for samples B and C, a 5 nm wide portion on the substrate and surface sides, respectively, of each well, were doped with Si at a level of 3×10^{15} cm^{-3} during growth. All surfaces had moderate to high densities of point defects with smooth backgrounds. Sample A was grown with In bonding, while the much thicker B and C were grown with In-free bonding.

Once grown, the samples were fabricated into photoconductors. Figure 2 shows a sketch of a typical device. The contacts were formed by fabricating dovetail recesses along the $\{0\bar{1}1\}$ planes with a wet etch (to a depth of $\sim 75\%$ of the layer thickness), evaporating Ni/Ge/Au in thicknesses of 30, 40, and 340 nm, respectively, and alloying the device at 450 °C for 30 s in a N_2 atmosphere. The oversized device was then cleaved into its finished size of 6×6 mm, and gold wires were attached using a conducting epoxy.

The contacts were specifically designed to cover the lower portion ($\{1\bar{1}1\}$ and $\{11\bar{1}\}$ B planes) of the dovetails. We tried to make photoconductors using contacts along the {111} A planes, but found the devices always exhibited megohm room-temperature resistances. This was not unexpected; Si has been found to incorporate as a *p*-type dopant on {111} A planes,[6] so the diffused Ge from the ohmic contacts here may also have incorporated on these planes as a *p*-type donor, preventing ohmic contact.

At room temperature, samples B and C were measured to have ~ 2 kΩ resistances, while sample A was measured to have ~ 20 MΩ resistance. Sample A, which was also used in earlier work,[2] was most likely depleted, owing to its relatively thin 2.0 μm thick active layer structure; at 4 K, external illumination was required before measuring the sample's spectra. Samples B and C behaved well at both room temperature and 4 K, indicating that thicker (14–16 μm) samples are preferred over thinner ones. The contact resistance of B and C was estimated to be ~ 220 Ω. Cur-

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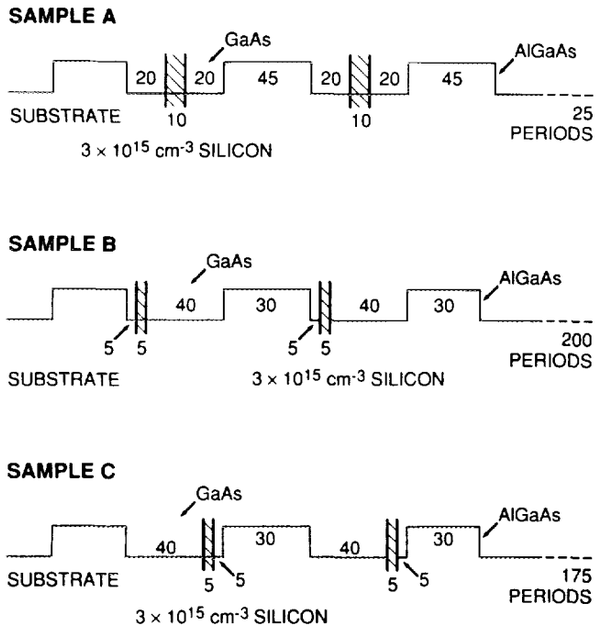

FIG. 1. Conduction band diagrams of samples A, B, and C along with intended doping positions and concentrations. All samples were grown with a substrate temperature of 680 °C.

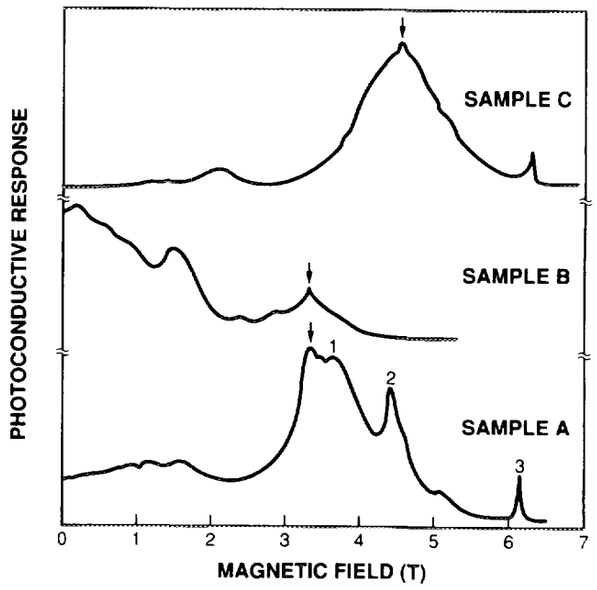

FIG. 3. Photoconductive spectra from the three samples of Fig. 1 obtained by sweeping the magnetic field during 84.94 cm^{-1} laser excitation. The $1s \rightarrow 2p_{+1}$ transitions of samples A and B occur at similar fields, while the transition of sample C is shifted to higher field. In the spectrum of sample A, peak 1 has been identified as a $1s \rightarrow 2s$ transition, peak 2 has been identified as a D^- transition ("helium transition"), and peak 3 is probably a transition between states of a well electron bound to a positive ion in the barrier.

rently, we are using the remaining material to fabricate two finger-structure designs, in order to improve responsivity and to better match sample resistance to electronic circuitry.

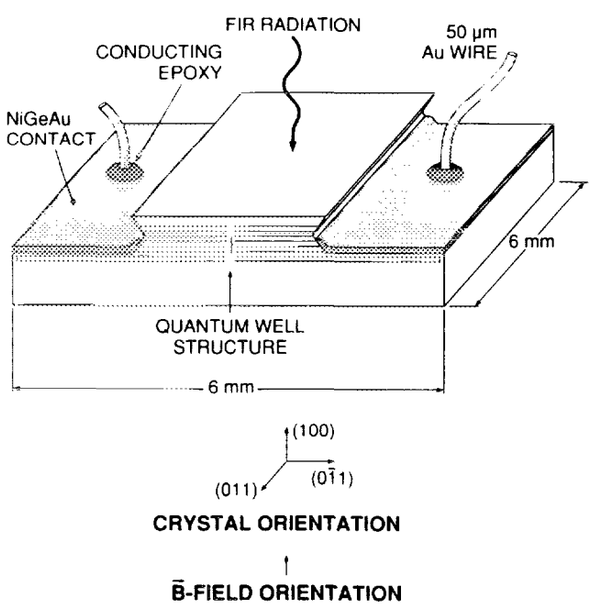

FIG. 2. Sketch of a typical photoconductor. The crystallographic orientation of the sample and the direction of magnetic field used during measurements are indicated.

The samples were placed in a superconducting solenoid and immersed in liquid He. The radiation was supplied by a CO_2-laser-pumped FIR gas laser. A brass light pipe was used to feed the radiation onto the sample. The magnetic field and radiation were oriented along the normal to the sample surface (Faraday geometry). The magnetic field of the solenoid was calibrated with a Hall probe. The experimental setup is further described in the literature.[2]

Photoconductive spectra were obtained by sweeping the magnetic field at a fixed laser frequency and monitoring the photoconductive response of the sample. Figure 3 shows the spectra produced by the three samples using an 84.94 cm^{-1} FIR laser source. The $1s \rightarrow 2p_{+1}$ transition is marked for each spectrum. The other peaks associated with sample A have been discussed elsewhere.[2,3,7] We mapped the magnetic field dependence of each of the three samples using a minimum of three laser frequencies. Plots of the magnetic field dependence of the $1s \rightarrow 2p_{+1}$ transition energy for the samples are shown in Fig. 4. The points are experimental data and the solid lines represent theory.

The photoconductors typically had resonant-wavelength responsivities of ~ 1 V W^{-1} with noise equivalent power (NEP) values of $\sim 1 \times 10^{-7}$ W $Hz^{-1/2}$. Although the NEP values are poor compared to 4×10^{-14} W $Hz^{-1/2}$, which was obtained in high-purity bulk GaAs,[8] we expect them to improve dramatically with minor modifications of the fabrication procedure. We suspect that most of the noise in these samples is due to contact noise. Experiments are currently under way to minimize contact resistance and to determine optimal finger spacing. We ex-

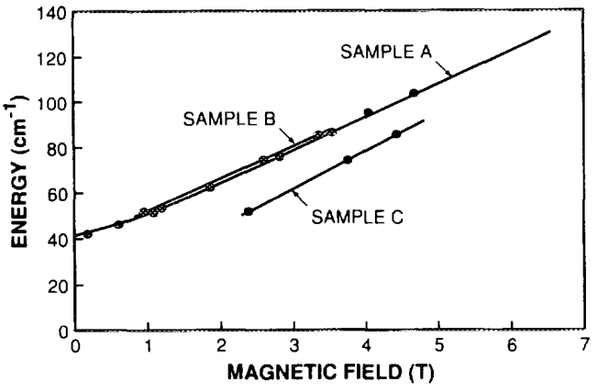

FIG. 4. Magnetic field dependence of the $1s \rightarrow 2p_{\pm 1}$ transitions of the three samples shown in Fig. 1, using a number of excitation energies. The points are experimental data and the lines are theoretical plots. The error between data and theory is $< 3.0\%$.

pect to be able to improve the NEP values of the devices by at least one or two orders of magnitude in the near future.

III. DISCUSSION

Comparisons of the spectra in Fig. 3 and the plots of Fig. 4 demonstrate that the $1s \rightarrow 2p_{+1}$ spectra from samples A and B are similar, while the spectrum from sample C is shifted to a higher magnetic field. Qualitatively, these results can be explained from Fig. 5, which shows a conduction band diagram of a wide quantum well with the $1s$ and $2p_{+1}$ levels of a central and off-center shallow donor indicated, along with plots of $1s \rightarrow 2p_{+1}$ transition energy versus well position at various magnetic fields. Donors located away from the center of the well require higher magnetic fields than those in the center to bring their $1s \rightarrow 2p_{+1}$ energies into coincidence with the laser.

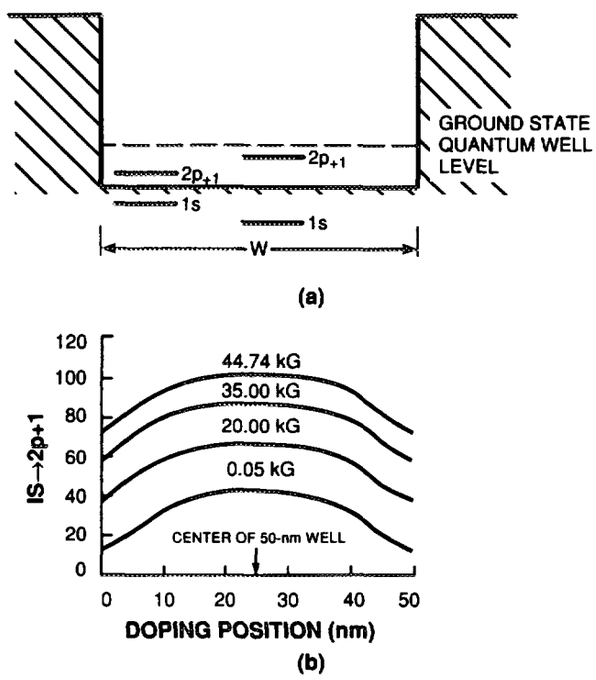

FIG. 5. (a) Energy levels of a donor at the center and near the side of a QW. (b) Plots of $1s \rightarrow 2p_{+1}$ transition energy vs well position at various magnetic fields.

Applying a variational theory for determining the energy of the $1s \rightarrow 2p_{+1}$ transition as a function of well width, well position, and magnetic field, we calculated that sample A is centrally doped with 51 nm wide QWs,[2] that sample B is centrally doped with 46 nm wide wells, and that sample C is doped 19 nm off center with 50 nm wide wells. Using scanning electron microscopy, we independently determined that the QWs of samples A and B are 50 nm thick with an error < 5 nm. Upon review of reflection high-energy electron diffraction data, sample B has been estimated to be 47 nm thick. The theory, shown as the solid lines in Fig. 4, agrees with the data with an error $< 3.0\%$.

If the value of the transition energy as a function of well position is taken into account, donors of sample B moved at least 10 nm from their intended position, while donors of sample A moved by at most 5 nm and those of C by ~ 3 nm. The substrate growth temperature, the growth technique, and the well/barrier interfaces all influence the position of the donors. The growth technique and substrate growth temperature determine the amount of evergy available to the donor migration process. At the same time, the top well/barrier interface appears to inhibit the migration, while the lower interface possibly aids the migration. Less of an effect is expected at lower substrate temperatures. Such behavior is quite different from that in bulk GaAs, where migration lengths are expected to be < 4 nm at these doping levels and growth temperatures.[9] The fact that an interface might inhibit migration is not surprising, since heterointerfaces have been used for impurity gettering for many years.[10] Currently, we are developing a theory and software that will allow us to convert a spectrum into a plot of concentration versus well position. Such a tool would complement capacitance–voltage techniques and secondary ion mass spectrometry by enabling us to accurately determine low doping and/or impurity concentrations as a function of position in a variety of heterostructure systems.

IV. SUMMARY

Shallow-donor QW photoconductors have been fabricated and measured to have FIR resonant-wavelength responsivities of ~ 1 V W^{-1}, with NEP values of $\sim 1 \times 10^{-7}$ W Hz$^{-1/2}$ at 4 K. The technology has been used to measure the position of Si donors in QWs at doping levels below those levels detectable by other means. With the use of a 680 °C substrate growth temperature, the actual position of the donors has been found to significantly vary from the intended position. Such measurements are useful in understanding the dynamics of doping incorporation in QW photoconductors, and the results are also applicable to commercially important devices such as high electron mobility transistors and pseudomorphic high electron mobility transistors.

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[1]N. C. Jarosik, B. D. McCombe, B. V. Shanabrook, J. Comas, J. Ralston, and G. Wicks, Phys. Rev. Lett. **54**, 1283 (1985).
[2]E. R. Mueller, W. D. Goodhue, D. M. Larsen, J. W. Bales, and J. Waldman, Phys. Rev. B **44**, 1754 (1991).
[3]E. R. Mueller, D. M. Larsen, J. Waldman, and W. D. Goodhue, Phys. Rev. Lett. **68**, 2204 (1992).
[4]S. Huant, W. Knap, G. Martinez, and E. Etienne, Europhys. Lett. **7**, 159 (1988).
[5]R. T. Grimes, M. B. Stannaway, J. M. Chamberlain, J. L. Dunn, M. Henini, O. H. Hughes, and G. Hill, Semicond. Sci. Technol. **5**, 305 (1990).
[6]W. I. Wang, E. E. Mendez, T. S. Kuan, and L. Esaki, Appl. Phys. Lett. **47**, 826 (1985).
[7]E. R. Mueller, Ph.D. thesis, University of Massachusetts Lowell, 1992.
[8]G. E. Stillman, C. M. Wolfe, and J. O. Dimmock, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer, (Academic, New York, 1977), Vol. 12, pp. 169–290.
[9]E. F. Schubert, H. S. Luftman, R. F. Kopf, R. L. Headrick, and J. M. Kuo, Appl. Phys. Lett. **57**, 1800 (1990).
[10]See, for example, P. M. Petroff, R. C. Miller, A. C. Gossard, and W. Wiegmann, Appl. Phys. Lett. **44**, 217 (1984).