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Characterization of a High Mobility, Sb Delta-Doped Structure Grown by Si-MBE

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Large enhancements in the electron mobility are reported for structures containing a pair of closely spaced Sb δ-doped layers in Si. The room temperature mobility is enhanced by a factor of two compared to corresponding uniformly doped layers or singly δ-doped structures. This is attributed to the flow of carriers in the central undoped region of the well where the impurity scattering is significantly reduced. Even higher mobilities were obtained by using a Schottky gate on top and applying a voltage to tilt the potential well. With a gate voltage of -1.5 V the mobility was 1200 $cm^2V^{-1}s^{-1}$ at room temperature, which is an enhancement by a factor of ten relative to the layer with equivalent bulk doping concentration. This may be assigned to relocation of electrons from the topmost δ-layer to lower lying layers.

I. Introduction

Modern semiconductor growth techniques have provided great possibilities to create thin doping layers with a thickness of a few atomic layers (δ-doping). δ-doped layers in Si MBE have been achieved by solid-phase epitaxy[1] and by ion beam doping[2]. The charge carriers are, in this case, confined in a self-consistent quantum well induced by the δ-doped layer. It has thus stimulated the interest to study electronic properties in such 2D-systems. However, due to strong ionized impurity scattering inside the doping layer, no improvement of the carrier transport has been observed in a singly δ-doped layer[3].

Recently, Zheng et al.[4], reported that enhanced carrier mobilities were observed in GaAs with doubly δ-doped layers. In this case, the two δ-doped wells are partly overlapping and for subbands associated with symmetric wave functions there will be an increased carrier concentration in the undoped region between the dopant layers. The reduced ionized impurity scattering can thus improve the electronic transport.

In this communication, we report, for the first time, the observation of enhanced electron mobilities at room temperature in doubly δ-doped Si structures. Furthermore, by connecting a Schottky gate to the front side of the structure, the amount of carriers transfered from the first δ-doped well to the lower lying layers can be modulated. The highest room temperature mobility, $\approx 1200\ cm^2V^{-1}s^{-1}$, has been achieved with a negative bias of -1.5 V for a sheet doping concentration of $2x10^{13}\ cm^2$.

II. Experiment

The samples were grown on p-doped substrates (4-20 Ω cm) in a Vacuum Generators V-80 Si MBE system with a base pressure of $5x10^{-11}$ Torr. After standard cleaning procedures the substrates were annealed *in situ* to remove the oxide of the surface to get a sharp 2x1 RHEED pattern. An undoped, 700 Å thick Si buffer layer was first grown at 750 °C. The antimony δ-doped layers were deposited by a low-energy ion beam (250 eV) at 650 °C for 15 min to reach a Hall carrier density of $1x10^{13}\ cm^{-2}$ per layer. A thin spacer of 120 Å between the δ-doped layers and a cap layer of 700 Å on the top were grown nominally undoped. The free electron concentrations obtained, averaged over the doubly δ-doped quantum well (≈200Å), correspond to a bulk concentration of $\approx 1x10^{19}cm^{-3}$.

Fig.1a shows schematically the layer structure of a sample with a Schottky gate on top. The corresponding band diagram is shown in Fig 1b.

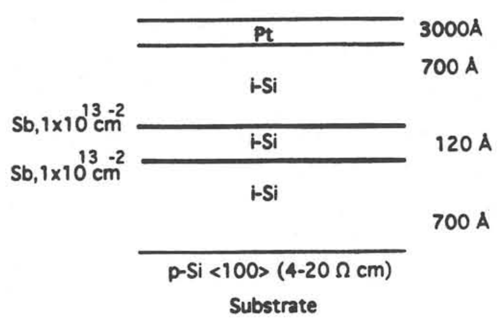


Fig.1.a. Schematic diagram of the layer structure.

No precipitates in antimony δ-layers or other extented defects in the top Si layers were observed by cross-sectional transmission electron microscopy for the samples used in the present experiments. Contacts for a van der Pauw configuration for Hall measurements and the Schottky gate were made using photolithography and lift-off techniques. A Au-Sb alloy was evaporated and annealed at 300 °C to achieve ohmic contacts and a Pt-Schottky gate with cross shape was formed. Electron concentrations and Hall mobilities were measured under a magnetic field of 0.25 T.

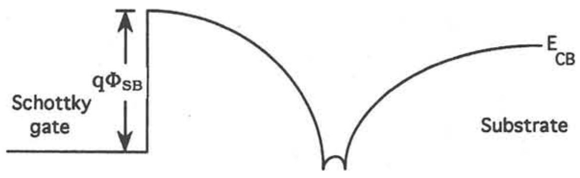


Fig.1.b. Schematic band diagram of the structure.

III. Results and discussion

Fig.2 shows the mobilities measured in singly[5] and doubly (d=120Å) δ-doped layers and a corresponding uniformly doped layer ($2x10^{19}$ cm^{-3}).[6] There is no improvement of the electron mobility with a singly δ-doped well. One reason is that both the lowest two sets of subbands in the δ-doped well, corresponding to the two-fold and four-fold degenerate bulk levels respectively, have maximum charge density at the plane of the dopant atoms. Thus the ionized impurity scattering for these bands may be even stronger than for the homogeneous doping case.

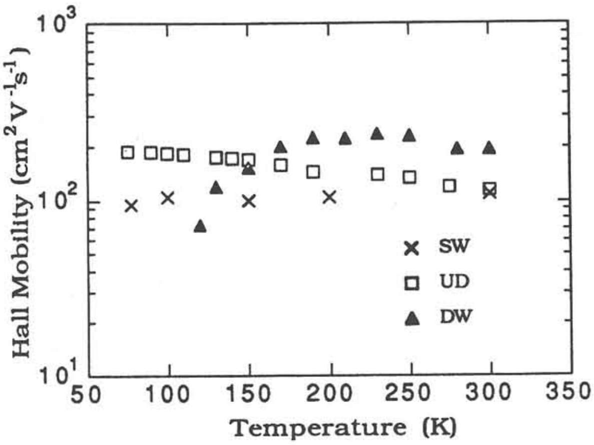
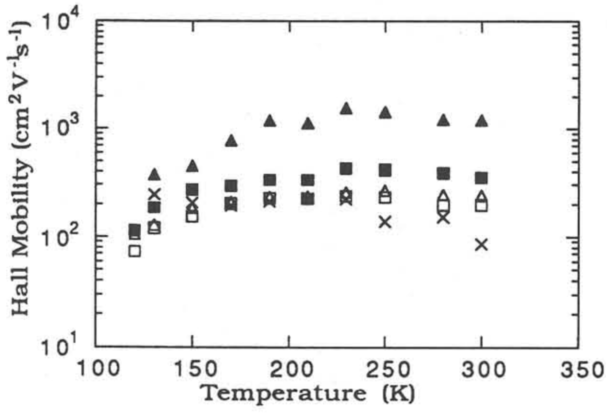


Fig.2. Hall mobilities for samples as a function of temperature. SW refers to the single well (H. Li et al.)[4], UD refers to corresponding uniformly doped layer $2x10^{19}$ cm^{-3} (P. Fons et al.)[5] and DW refers to the double well with 120 Å spacer between the δ-doped layers.

In the doubly δ-doped well, the situation is quite different. For a symmetric potential the lowest sets of the two-fold and four-fold subbands should correspond to symmetric wave functions with enhanced carrier concentration in the undoped region between the two sheets of dopant atoms. At room temperature there is a factor of two enhancement of the electron mobility as indicated in Fig.2. As the temperature is reduced, the mobility drops down to the level of a singly δ-doped layer. We tentatively assign this to transfer of electrons from delocalized excited states to states more localized near the sheets of dopant atoms.

Since the surroundings of the doubly δ-doped layer are not completely symmetric we can use a Schottky gate on top to compensate for some asymmetry. If the enhancement of the mobility was very sensitive to the symmetry of the potential we would expect a maximum mobility for a small bias. Fig.3 shows the variation of electron mobility over different temperatures and gate voltages.



(□) V_G=0 V, (■) V_G=-1 V

(△) V_G=-0.5 V (▲) V_G=-1.5 V

and (×) V_G=-2 V.

Fig.3. Hall mobilities as a function of temperature for different gate voltages.

At room temperature the mobility monotocally increases with negative gate voltage to a maximum at V_G =-1.5 V, that corresponds to an enhancement with a factor of ten relative to a single δ-layer.

By changing the gate voltage we bend the well and eventually push electrons from the first δ-doped well down into the second δ-doped well and the undoped spacer layers. Consequently the carriers will suffer less Coulombic scattering from the impurity centers in the second δ-doped well due to the improved screening. Associated with the large enhancements in mobility we measure only small variations in the electron sheet concentration as shown in Fig.4. This is consistent with a mere shifting of the wave functions in the full doubly δ-doped quantum well. When V_G is further decreased to less than -1.5 V both the mobility and sheet concentration decrease rapidly. This is possibly due to the increase leakage current through the Schottky gate which may degrade the performance of the device structure.

The measured temperature dependence of the mobility shows that practically the whole mobility enhancement is obtained at room temperature. There is generally a weak maximum at T≈250 K (1500 $cm^2V^{-1}s^{-1}$) and then the mobility drops with decreasing temperature. Since the temperature affects the shape of the quantum well, the occupancy of bands, as well as the scattering mechanisms, it is presently difficult to isolate the various contributions to the temperature dependence of the mobility.

The temperature dependence of the mobility at the highest negative bias (-2V) is different from the cases with lower bias. This is consistent with the interpretation of the detrimental effect of tunneling current from the Schottky gate at room temperature which then is suppressed at lower temperatures.

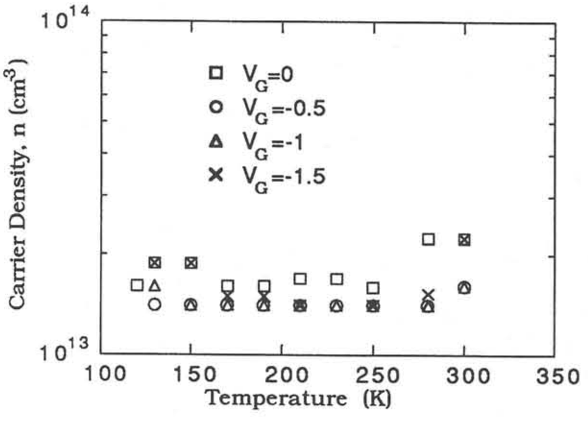


Fig.4. Carrier densities as a function of temperature for different gate voltages.

Acknowledgement

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