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ELECTRONIC STATES AND TRANSPORT PROPERTIES OF AN n-TYPE δ-FUNCTION DOPING LAYER IN p-TYPE Si

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Résumé
Des couches bien définies et extrêmement minces d'atomes de Sb ont été introduites dans le Si de type p pendant la déposition par MBE.
Nous avons mesuré le transport paral-\(\text{x}\)elle et perpendiculaire à la couche dopée.
Ainsi nous avons déterminé les niveaux électroniques des sous-bandes 2-dimensionelles.

Abstract
An extremely sharp and well-defined sheet of Sb-dopant atoms can be embedded in Si with high p-type background during MBE growth.
We have measured the transport parallel and perpendicular to the doping layer. The electronic levels of 2-dimensional subbands have been detected.

Introduction
For various electronic applications, such as the camelback diode and transistor devices, it is required to have extremely sharp and abrupt high density doping profiles. In Ref. /1/ we have shown how an n-type Sb-layer in Si can be incorporated in an epitaxial layer during MBE growth. The method involves a stop and grow procedure whereby Sb ions are deposited after the growth has been interrupted and the layer cooled to room temperature. The Sb is subsequently covered with \(\sim 30 \, \text{Å}\) of amorphous Si and finally recrystallized at the growth temperature of 700\(^0\) C when growth is continued. In this manner a doping layer of Sb atoms has been achieved that extends only a few lattice planes in the growth direction.

In earlier work the so-called δ-doping layer has been embedded in weakly p-type (2 \(\times\) \(10^{16}\) cm\(^{-3}\)) material. Quantized electronic subbands have been observed that confirm the sharpness of the layer. In addition the sharp Sb doping layer has been observed directly in a TEM bright field image.

Present work has aimed to produce the n-type Sb layer next to strongly p-type material in order to simulate the conditions necessary in devices where on the scale of a few 100 Å the potential is to rise rapidly. The unoccupied electronic subbands above \(E_F\) are to be confined by the p-type depletion barrier potential and not in a near accumulation situation such as in the previous work. Our concern in this work has been to study the transport in the layer and via tunneling currents normal to the layers.

Experimental Notes
A large number of δ-layer samples with different Sb density has been grown in succession in order to establish the technique of solid phase epitaxy. Doping levels of \(10^{15}\) to \(10^{19}\) cm\(^{-2}\) have been given for the conductivity studies. The number of Sb atoms actually incorporated during the growth is not known precisely.
Fig. 1: Bright-field TEM image of an Sb δ-doping layer with density 5 x 10¹³ cm⁻³ and 200 Å distance from the Si surface.

Fig. 2: Resistance per square vs. Nₛ from Hall measurements for many different δ-layer samples. The transition to an insulating state occurs just below ~1 x 10¹³ cm⁻².

The sharpness of the layer that has been achieved is illustrated most convincingly by the bright field TEM images. Fig. 1 is an example with an Sb areal density of 5 x 10¹³ cm⁻². The dark band shows it to be confined to ~2 nm. The estimated resolution of the microscope is itself limited to scattering of the order of 1 nm. A controlled thickness of surface layer (~20 nm) is subsequently added after the solid phase epitaxy to achieve the right magnitude of tunneling resistance to the surface Schottky barrier contact. The peaked doping profile seen in the figure is certainly much sharper than could be measured by SIMS. The latter technique has been used to provide a count of the Sb atoms for comparison with the electrically measured density of active dopant.

In order to achieve an abrupt and high density p-n junction, we proceed as follows. MBE growth is carried out in the presence of a Ga flux from an effusion cell. The partial pressure is such as to produce ~10¹⁸ cm⁻³ p-type material in calibration experiments. It is well known that because of segregation the growing surface is covered under these conditions with a very high concentration of Ga atoms. When interrupting the growth we first heat the sample to 900°C from its growth temperature (~700°C) to drive off excess Ga. This step is followed by the room temperature deposition of the Sb δ-layer.

Result and Discussion

For high density of Sb atoms in the δ-layer the electron system is degenerate. The electronic levels form a set of 2-dimensional subbands in a V-shaped potential well.

We have studied both the Hall effect and surface resistivity of many δ-layer samples in order to characterize their electrical properties and to learn how the nominal Sb concentration introduced during growth relates to the measured carrier density Nₛ. Fig. 2 shows the results of ρₓ vs. the measured Hall density Nₛ. Samples are such that the Sb-layer is embedded in nominally undoped background material, sufficiently far from the surface in order to avoid significant carrier transfer to the surface. We note the sharp rise of the resistance at low Nₛ indicating the
transition to an insulating state. The average separation for the critical density is $\sim 30 \text{ Å}$. The Hall densities $N_S$ do not necessarily measure correctly the electron concentration in the δ-layer because two or more subbands are occupied. The subband electrons have different transport masses and mobilities. Measurements that compare the total SIMS Sb concentration with the Hall density are in progress.

In order to characterize the sharp p-n junction we have chosen to examine the tunneling current flowing from the δ-layer to a surface Schottky contact (see insert in Fig. 3). Such measurements have previously been carried out for δ-layers in GaAs /2/ and in our previous work /1/. The steepness of the potential well is characterized best by examining the unoccupied electronic levels above $E_F$. These are seen for electron currents tunneling into the doping layer from the metal contact for negative values of the Schottky gate potential. Fig. 3 shows an example of such a tunneling spectrum. The sample has a δ-layer with design doping of $\sim 2 \times 10^{13} \text{ cm}^{-2}$ Sb on a p-type background of $1.0 \times 10^{18} \text{ Ga cm}^{-3}$. The Schottky barrier contact is made by evaporating Ni-Cr and Ag. The contact has a typical barrier height of 0.65 eV.

The $dI/dV_g$ structures in Fig. 3 are particularly clearly resolved for negative $V_g$ as expected. Only weak tunneling conductivity structures identify the occupied levels for positive $V_g$. The situation is similar to that found by Kunze /3/ for tunneling into the Si-MOS structures in the presence of a strong substrate bias potential.

We proceed with the analysis of the data in Fig. 3 by calculating the potential profile and subband levels for the known p-type doping and the expected surface barrier potential ($\sim 0.65 \text{ eV}$). The number of δ-layer electrons corresponding to the density of $2 \times 10^{13} \text{ Sb atoms}$ is adjusted to produce the fit of levels to the $dI/dV_g$ structures as indicated by arrows in Fig. 3. The marks are corrected with regard to the change of the energy levels when a gate voltage is applied.

In Fig. 4 the calculation of the potential and subband structure with a gate voltage of 200 mV and $N_S$ value of $1.3 \times 10^{13} \text{ cm}^{-2}$ is shown. Levels 0 and 0' are found to be occupied. $0.7 \times 10^{13} \text{ cm}^{-2}$ electrons are lost to the depletion charge and the Schottky gate. The levels are labelled in accordance with the nomenclature established for MOS inversion layer subbands on (100) Si. Their degeneracies are respectively $g_v = 2$ and 4 for the unprimed and primed numbers. The subband energies of 0 and 0' are very sensitive to the spread of the δ-doping. Spreading fluctuations in

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**Fig. 3:** Tunneling current derivative $dI/dV_g$ as observed for the δ-layer sample. The subband energies are marked according to the calculation.

**Fig. 4:** Potential distribution and energy levels for the δ-layer sample with p-background doping of $1.0 \times 10^{18} \text{ cm}^{-3}$. 
this case may account for the missing of these levels which were seen clearly in previous tunneling spectra /1/. Insofar as the calculation for Fig. 4 reproduces the $dI/dV_g$ structures seen in the experiments it provides a measure of the potential profile in the surface p-n junction region.

When a structure such as employed here is illuminated with band-gap light one expects the $dI/dV_g$ peaks to shift, because the p-n junction potential is reduced under nonequilibrium conditions. For the present example the light effect is quite small. This can be understood by considering the valence band and acceptor states also shown in the diagram. For the high doping levels the junction width is so small that extra electrons due to the illumination in the higher subbands are rapidly lost by tunneling to neutral acceptor states under the nonequilibrium conditions. It follows that it is more difficult to perturb the electronic states in such a sharp doping profile.

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