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Low Temperature Characteristics of Ambipolar $SiO_2/Si/SiO_2$ Hall-bar Devices

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1. Introduction

Physical properties of silicon governed by quantum mechanics will prove progressively prominent due both to continued miniaturization and the drive toward silicon based quantum information processing. The technological sophistication afforded by silicon can also be expected to offer fertile ground for basic experimental physics as novel physical conditions can be attained with high controllability.

One of the most basic quantum mechanical structures is the quantum well where two potential barriers confine carriers in a narrow but two-dimensionally extended region. Such a structure is readily realized in thin SOI (Silicon-On-Insulator) MOSFETs and this is the subject of this work. In order to extract intrinsic transport properties such as resistivity, which forms the basis of much physical analysis, the quantum well under investigation can be patterned into a Hall-bar geometry. Recently, Hall-bar devices with n-type Ohmic contacts have been used to investigate effects such as those due to quantum confinement and valley-splitting [1-3].

Here, we present basic low temperature characteristics of $SiO_2/Si/SiO_2$ Hall-bar devices where each arm of the Hall-bar is split into p-type and n-type Ohmic contacts made by selective area ion-implantation doping of boron and phosphorus respectively. We show that such devices demonstrate considerable potential for examining a variety of physical situations.

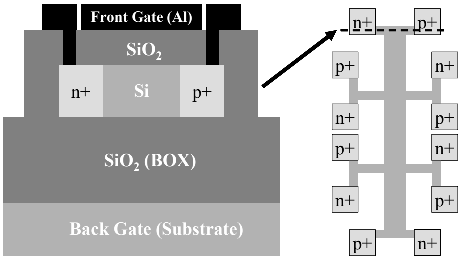

Fig. 1 Schematic diagrams of the samples. Right: The Hall bar geometry. Left: A cross-section along the dashed line.

2. Device Preparation

A SOI wafer of appropriate silicon thickness is prepared by repeated thermal oxidation and selective etching. This is then followed by gate-oxidation and mesa-etching, to define a $SiO_2/Si/SiO_2$ quantum well in the Hall-bar geometry. A combination of silicon-over-etching and further oxidation is utilized to prevent edge-leakage or extra channel formation at the mesa edges. As shown in Fig. 1, each arm of the Hall bar is spit into two branches. Each branch is heavily doped by ion-implantation with either phosphorus or boron in order to define n-type or p-type regions. The samples are then pulse-annealed to activate the dopants. Holes are etched in the oxide above the doped regions where aluminium is deposited to form contacts in the standard way. Aluminium is also used as the gate metal.

3. Results

Any pair of p or n-type contact can be chosen to obtain standard MOSFET characteristics. Fig. 2 shows the drain current for both the n-channel and the p-channel at various values of back-gate voltage V_{BG} for a sample with a nominal SOI thickness of 22nm.

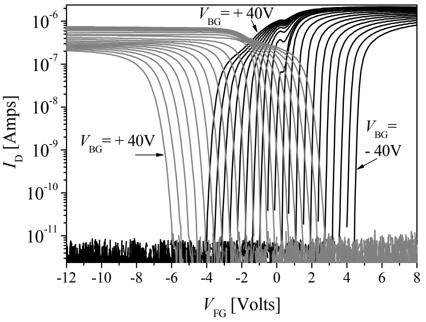

Fig. 2 Current through pairs of n-type (black) and p-type (grey) contacts at 1.4K with a drain bias of 10mV.

Since the regions forming the Ohmic contacts are heavily doped, they are relatively unaffected by the gate voltages. Thus when there is a 2DEG (2-dimensional electron gas) in the quantum well, the phosphorus doped regions form good Ohmic contacts to the 2DEG, while the line interface to the boron doped region forms a lateral pn-junction (2DEG-3DHG junction). At cryogenic temperatures, therefore, under conditions of small source-drain bias (<<1V), p-type contacts are isolated from the 2DEG. Similarly, when there is a 2DHG (2-dimensional hole gas) in the quantum well, p-type contacts form good Ohmic contacts while n-type contacts are isolated.

Structure can be seen in the curves for both p and n channels due to the formation of 2DEG or 2DHG at the front or back interfaces. For instance, there is a shoulder/peak near V_{FG}=0V for the electrons. This can be confirmed using standard magneto-transport measurements.

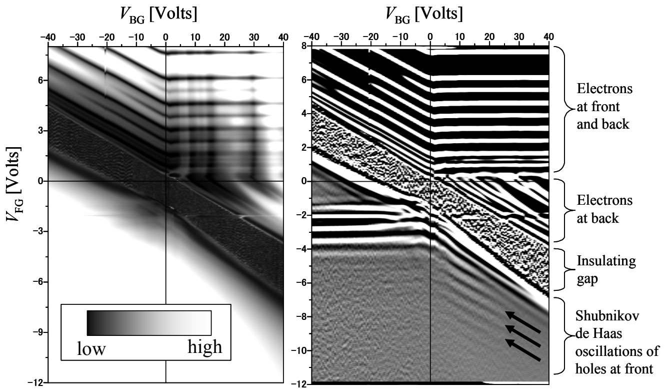

Fig. 3 Left: grey-scale plot of the sheet conductivity at 8T, 1.4K as functions of the front and back gate voltages. (An AC lock-in technique was used to make four terminal measurements of R_{xx} and R_{xy}.) Right: A double differential has been taken with respect to V_{FG} in order to highlight the oscillations due to the holes at the front interface (some marked by arrows). Distinct regions can be seen corresponding to (clockwise from top-right) electrons at front and back, electrons only at the back, insulator, holes at the front, holes at front and back, holes only at the back, insulator and electrons at the front.

Fig. 3 (left) shows the sheet conductivity at a magnetic field of 8T, 1.4K. Clear Shubnikov de Haas oscillations can be seen for electrons at the front and back interfaces [1], while they are not so pronounced for the holes. This is in part due to the large effective mass of the heavy holes reducing the cyclotron energy. We have confirmed that at higher magnetic field and lower temperature, well formed quantized Hall states can be observed for both electrons and holes. Fig. 3 (right) shows a double derivative of the data in Fig. 3 (left) where clear oscillations are also visible for the holes.

Electron and hole concentrations can be extracted, either by Hall-effect measurements or Shubnikov de Haas oscillations and resistivity can then be used to map out mobility for both electrons and holes. Due to the differences in effective mass, the wavefunction for the heavy holes should be closer to the Si/SiO$_2$ interfaces, compared with the electrons, and may allow further information to be extracted concerning the interfaces.

The data also reveals a variation of conduction threshold which is not parallel in (V_{FG},V_{BG}) to lines of constant concentration, reflecting changes in localization with bias of the confinement potential. Furthermore, changes in the patterns due to Shubnikov de Haas oscillations suggest considerable changes in the spin-splitting of the heavy holes with potential bias.

Varying the SOI thickness also offers new possibilities. When the quantum well is wide, both a 2DEG and 2DHG can be generated simultaneously at opposite interfaces where the two types of doped regions form independent contacts to the two conducting layers [Fig. 4, two panels on the left]. This will allow measurements of electron-hole drag. Moderate bias can be applied between the electron and hole layers without any current flowing between them allowing additional control over concentrations and electric field. Furthermore, the system constitutes a novel vertical pn diode where the p and n-type regions are defined by a 2DHG and 2DEG respectively.

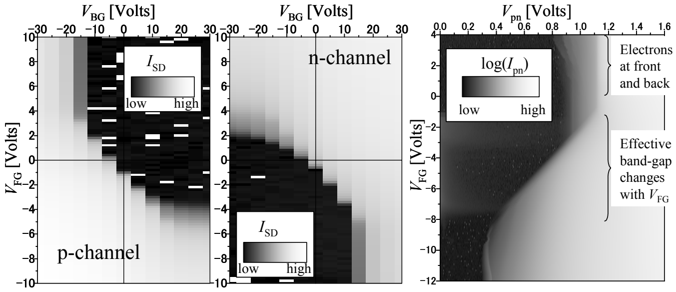

Fig. 4 Left two panels: grey-scale plots of the source-drain current through a 70nm thick SOI device. Two regions (top-left and bottom-right) in (V_{FG},V_{BG}) can be seen where a 2DEG and 2DHG coexist. Right: Current between n and p-type contacts with all other contacts floating in a 22nm thin SOI sample, V_{BG}=70V, 1.4K.

When the quantum well is narrow, on the other hand, conditions can be found with considerable electron-hole recombination at moderate pn bias. The 2DEG-3DHG (or 2DHG-3DEG) forms a pn-junction where the effective band-gap can be tuned by controlling the gate voltages. Figure 4 (right) shows current between p and n type contacts measured with all other contacts floating. A range of V_{FG} is seen where there are electrons at the back interface and no 2D carriers at the front and the source drain voltage V_{pn} required for the onset of current decreases with decreasing V_{FG}.

3. Conclusions

Ambipolar SiO$_2$/Si/SiO$_2$ devices offer many opportunities for examining the physics of SiO$_2$/Si/SiO$_2$ quantum wells. Not only can the physics of 2DEGs, 2DHGs and Si/SiO$_2$ interfaces be explored, but separately contacted electrons and holes may allow drag experiments and narrower quantum wells allow various novel transport measurements of electron-hole recombination.

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