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Transport spectroscopy of single Pt impurities in silicon using Schottky barrier MOSFETs

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Abstract

We investigate low temperature electron transport in silicon Schottky barrier metal–oxide–semiconductor field-effect transistors (MOSFETs), which consist of PtSi metallic source/drain electrodes. Measurements are made on approximately 23 inversion layers and resonances attributed to single impurities close to the metal/semiconductor interface are observed. We ascribe these impurities to Pt atoms that have diffused into the semiconductor channel from the contacts.

Current interest in understanding transport through individual impurities in silicon is motivated by the possibility of using dopants as qubits [1, 2] and by Si transistors made so small that transport can be significantly altered by a single impurity. Recent experiments have demonstrated transport spectroscopy of single dopants with unprecedented accuracy [3–7]. Our research uses a novel MOSFET with tunneling source and drain contacts [6, 7] made of the metallic silicide PtSi, as depicted in figure 1(a). Although the size of the transistor can result in different transport regimes [8], the ability to perform detailed spectroscopy on single impurities is possible for devices ranging from micron to nanometer sizes. In this paper we discuss an extensive series of measurements on silicon inversion layers and show that Pt impurities are a likely source of dopant atoms close to the metallic contacts.

1. Background

Transport spectroscopy of single impurities in semiconductors has been a topic of research for many years. Experiments typically fall into two groups: (a) resonant tunneling through single impurities situated in a tunnel barrier and (b) resonant tunneling through single impurities in a confined region of a semiconductor. In the first case a resonant peak is observed, superimposed on a background current [9]. In detailed explorations of deliberately introducing defects, one can account for these resonances and investigate their transport [10]. This line of research is typically hampered by the inability to apply a gate voltage, and the bias voltage that is applied to investigate the resonance can distort its shape. In the 1990s researchers found that single impurities could be explored in a much cleaner system: the resonant tunneling diode [11]. Topics that were investigated included transport through clusters of impurities [12], spin degeneracy of a localized state [13], the Fermi edge singularity [14] and impurities with two bound electrons [15].

Resonant tunneling through single impurities in a three-terminal device in which a gate electrode can be used to energetically sweep through the resonant level at zero bias affords a distinct advantage for spectroscopy. Such effects in MOSFETs were definitively demonstrated in 1986 by Fowler *et al* using transistors with a ∼1 μm width and a 0.5 μm channel length [16]. Research by Kopley *et al* used a split-gate MOSFET to investigate how a magnetic field could alter the tunneling rates [17]. A MESFET geometry has also been used to explore transport and interaction effects involving two impurities in GaAs/GaAlAs structures [18–20].

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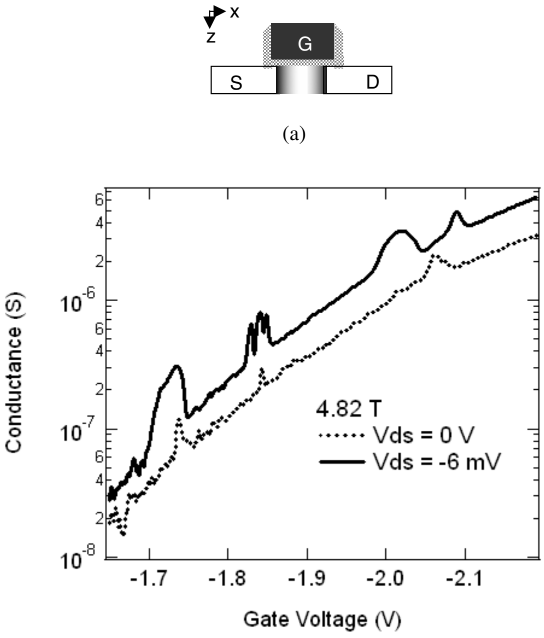


(a)

(b)

Figure 1. (a) Schematic of the Schottky barrier MOSFET. The source and drain consist of PtSi metallic contacts and the gate of 34 Å SiO_2. This is a long channel device and the depletion regions arising from the metal/semiconductor potential are indicated in a grayscale plot, between the source and the drain. (b) Differential conductance versus gate voltage for an inversion layer. The channel width and length are 20 μm and 5 μm respectively.

This line of research is similar to experiments that investigate single defects via random telegraph noise (RTS) [21]. In MOSFETs RTS is typically attributed to defect states near the Si/SiO_2 surface. Recent research has shown that RTS amplitudes can be significantly affected by single impurities [22, 23]. In addition RTS attributed to a single impurity has been reported, in a resonant tunneling diode [24]. A unique line of research has used RTS in MOSFETs to demonstrate electrically detected single-electron spin resonance of a defect [25–27]. RTS is sometimes observed in the SBMOSFETs considered in this paper and can significantly shift the energetic position of single impurities. The exact details depend on the proximity of the defect causing the RTS relative to the impurity.

Current research has investigated single impurities in very small MOSFETs. Sellier *et al* showed that excited state spectroscopy could be performed on shallow donors in a Si FinFET and demonstrated that the excited and first charge states could differ significantly from the bulk [3]. Ono *et al* have shown how a single impurity can modulate the conductance in a very small MOSFET [4] and in related work Khalafalla *et al* have demonstrated impurity coupling [5]. Recent research has also explored the transfer of single electrons between two phosphorus impurities [28]. Closely related to investigations of single impurities in transport are recent electron paramagnetic resonance experiments that are able to probe many impurities in a small sample region [29–32].

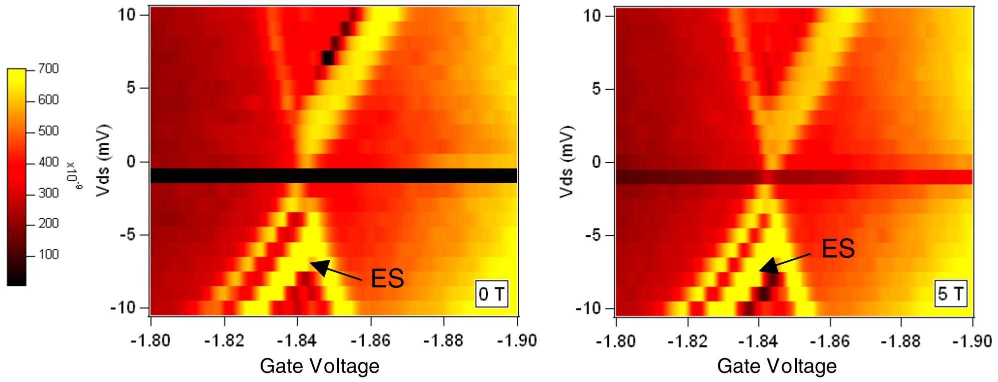
In a Schottky barrier MOSFET transport at low temperatures is dominated by tunneling through the depletion width formed at the metallic/semiconductor interfaces at the source and drain [33, 34]. When the energy level of a single impurity situated near the metal/semiconductor interface falls into the transport window, resonant tunneling occurs. Our research on single impurities in accumulation layers has shown that the ground state of a shallow acceptor can be split in the presence of a large electric [7] or strain field [8]. Here we summarize data from an extensive investigation on inversion layers and show that impurities are also observed in these devices.

2. Experimental details

The fabrication of SBMOSFETs is simplified compared to a traditional sub-micron MOSFET process. Devices were fabricated on standard (001) wafers with transistor transport along the $\langle 110 \rangle$ direction. Here a simple growth pattern and an etch back technique were used. The 34 Å gate oxide was grown in an ambient of dry oxygen in a rapid thermal processing furnace. Phosphorus doped amorphous silicon was deposited by CVD for the gate stack. The gate lithography and subsequent etch followed a proprietary process at National Semiconductor. A rapid thermal oxidation (RTO) of 15 (wafer A) or 6 (wafer B) seconds and subsequent etch resulted in the formation of oxide sidewalls on the gate stack. Platinum was deposited by DC sputtering and silicided with the underlying silicon during a one-hour anneal in nitrogen ambient at 450 °C. Remaining Pt was stripped using *aqua regia*. Further details of the processing and room temperature operation can be found in [35]. Measurements were performed in either a variable temperature cryostat at 4 K using a semiconductor parameter analyzer (Agilent 4145 or 4156) or in a dilution refrigerator at 40 mK using a standard lock-in technique at 36 Hz and an excitation voltage of 50 μV. The measurements span a ten-year period but no degradation or changes were found in the device characteristics. Magnetic field was applied parallel to the plane of the sample. The transistor characteristics investigated here were fabricated on n-type substrates. We observed Schottky barrier heights, between the source/drain and silicon channel, of ~0.2 eV, as measured from the current I versus gate voltage V_g characteristics as a function of temperature [36]. We investigated 7 transistors from wafer A and 16 from wafer B. We note that the MOSFET characteristics at room temperature of wafer B exhibited enhanced leakage through the substrate [37]. At low temperatures the characteristics of devices from these two wafers are indistinguishable. This is consistent with the earlier results because dopants in the substrate are frozen out at such low temperatures.

3. Results

In figure 1(b) we show the differential conductance G versus gate voltage V_g for a 20 μm width by 5 μm length device from wafer B. The data set is shown at finite magnetic field in order to suppress the superconductivity in the PtSi electrodes that occurs below 1 K. At source–drain bias $V_{ds} = 0$ V, three resonant peaks are observed, at $V_g \approx -1.74$ V, $V_g \approx -1.84$ V



(a) (b)

Figure 2. Differential conductance versus gate voltage for the n-substrate device in figure 1(b) at 0 T (a) and 4.82 T (b). The excited state is noted in the figure.

(This figure is in colour only in the electronic version)

Table 1. Summary of measurements from wafers A (a) and B (b).

Width/length (μm)	T (K)	V_g range (V)	# Impurities
(a) Wafer A			
$2.4/0.05 \pm 0.02$	4	-1.4 to -2.0	1
5/0.3	4	-1.4 to -2.0	1
20/1.7	4	-1.5 to -2.0	2
20/1.7	4	-1.5 to -2.0	2
20/1.7	4	-1.5 to -2.0	2
$20/0.05 \pm 0.02$	4	-1.5 to -2.0	0
$20/0.05 \pm 0.02$	4	-1.7 to -2.0	1
(b) Wafer B			
$0.2/0.05 \pm 0.02$	0.9	-1.75 to -2.5	1
0.3/20	0.05	-1.75 to -2.5	2
0.3/20	0.05	-1.75 to -2.5	1
5/0.3	0.05	-1.75 to -2.75	1
5/0.3	4	-1.5 to -2	1
10/0.7	4	-1.5 to -2.4	0
$20/0.05 \pm 0.02$	0.05	-1.6 to -2.5	0
$20/0.05 \pm 0.02$	0.05	-1.75 to -2.5	3
20/0.18	1	-1.75 to -2.5	2
20/0.18	0.9	-1.75 to -2.5	2
20/0.24	0.8	-1.75 to -2.5	5
20/1.7	0.05	-1.5 to -2.5	7
20/1.7	4	-1.5 to -2	1
20/1.7	4	-1.5 to -2	5
20/5	0.05	-1.5 to -2.2	4

and $V_g \approx -2.06$ V. Each peak is attributed to a different impurity located in the Schottky barrier. We observed ≈44 resonant peaks in 20 of the 23 devices measured. In table 1 we summarize the device size, number of impurities, V_g range investigated and temperature of observation for these devices. Although resonances are sharper at lower temperatures, they are often visible by 4 K. Intrinsic linewidths are generally reached around 300 mK. While some of the devices have resonances that are much larger than the background current, the majority are very small perturbations.

Of the three resonant peaks in figure 1(b), two are rather broad and we concentrate on the one centered at gate bias $V_g \approx -1.84$ V. At $V_{ds} = -6$ mV we observe an additional peak due to an excited state. Note that the increase in the differential conductance at the bias voltages is mainly due to changes in the density of states of the semiconductor [8]. To investigate the resonance in greater detail, we plot in figure 2 $\partial I/\partial V_{ds}$ versus V_g for many values of V_{ds} at both 0 T (a) and 4.82 T (b). Extending the excited state that we observe in the negative bias voltage to $V_{ds} = 0$ V, we find that it corresponds to an energy of 0.018 mV (≈2.7 meV) above the ground state. Typical excited states of these impurities range between 0.015 and 0.03 mV. The origin of this state will be discussed in further research. We perform a linear regression of the resonant peak position as a function of V_{ds} in figure 2(a) and (b) and find that at 5 T both the ground and excited state resonances are displayed to more negative values of V_g.

4. Discussion

We find that inversion layer devices exhibit a distinct resonant state. This impurity has an excited state at ∼20 mV above the ground state, unlike accumulation layers where an excited state is typically observed at ∼5 mV relative to the ground state. From table 1, we observed that the number of impurities present in the inversion layer does not scale with transistor size as was reported for accumulation layers [7]. In a recent series of measurements on ∼25 accumulation layers at 50 mK, we sometimes observed resonances that have excited states similar to the one observed here; however, overall impurities with excited states at ∼5 mV above the ground state are much more common.

We believe that the impurity state in inversion layers is likely due to Pt atoms that have randomly diffused into the barrier from the source and drain. Pt impurities in silicon have been the subject of many investigations ([38–42] and references therein). Pt has a well known deep donor level at $E_v + 0.330$ eV and deep acceptor level at $E_c - 0.243$ eV. Researchers have also identified a double-donor level at $E_v + 0.067$ eV [39]. This level was investigated using deep level transient spectroscopy (DLTS) but is not amenable to electron paramagnetic resonance studies. Therefore a detailed investigation of the energy spectrum of this level has been investigated neither theoretically nor experimentally. It is precisely this resonance that we believe to be the origin of the resonant state observed here, because other defects due to for instance platinum–oxygen or hydrogen complexes exhibit levels that are much deeper in the band gap [41, 42]. A double donor level is consistent with the change in peak position as a function of magnetic field because a second filled impurity should move higher in absolute energy, in this case towards the valence band edge [3]. While this research is undertaken in inversion layers, which allow us to investigate only Pt impurities, it is important to note how such an impurity can be distinguished from a shallow B acceptor in an accumulation layer. A double Pt donor is moves in a direction *opposite* to that of a shallow boron acceptor, which when singly occupied moves away from the valence band edge. However, a *double* boron acceptor would have the same motion as a function of magnetic field. It may be that the g-factor of a double Pt acceptor will allow its differentiation from that of a double boron acceptor [43].

5. Conclusion

In this paper we have shown that impurity resonances can be observed in inversion layers in SBMOSFETs. We attribute these resonances to Pt impurities that have diffused into the depletion region from the metallic contacts. We report that such resonances are also visible in accumulation layers but that they are distinguishable from shallow acceptors through the Zeeman effect and their excited states. Further research could investigate the dependence of the energetic spectrum on changes in the transport and magnetic field orientation in order to probe in further detail the nature of the impurity.

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