

A silicon radio-frequency single electron transistor at 4.2K

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Abstract— We report the demonstration at 4.2K of a silicon radio-frequency single electron transistor (rf-SET) fabricated in a complementary metal-oxide-semiconductor (CMOS) compatible architecture. Charge sensitivities of better than $10\mu\text{e}/\sqrt{\text{Hz}}$ are demonstrated at MHz bandwidth at mK, and charge sensitivity of the order $20\mu\text{e}/\sqrt{\text{Hz}}$ is achieved at 4K. These results demonstrate that silicon may be used to fabricate fast, sensitive electrometers for use at 4.2K.

Keywords—silicon; radio-frequency single electron transistor (rf-SET); tunnel barriers

I. INTRODUCTION

Electrostatically defined tunnel barriers are a flexible and powerful tool for the creation of single electron devices. Tunable tunnel barriers have facilitated the recent achievements of the manipulation of single electron spins in GaAs quantum dots [1-3]. Tunable barriers have also been used to create well-defined quantum dots in other low-dimensional systems, for example semiconducting carbon nanotubes [4,5] and InAs nanowires [6]. Recently tunable barriers have also been used to successfully define single electron devices and quantum dots in silicon [7 – 9]. Silicon is a particularly attractive material in which to investigate the coherent behaviour of single electrons, due to the expected long electron spin coherence time.

Fast charge detection is also a critical tool in the field of single electron devices. The single electron transistor is a very sensitive electrometer due to the sharp transconductance of the Coulomb blockade oscillations. The sensitivity of the conventional SET however is limited at low frequencies by $1/f$ noise and at high frequencies by its long time constant resulting from the high impedance of the SET and the capacitance of the lines. The rf-SET however utilises radio-frequency reflectometry in order to transform the high impedance of the SET [10]. This technique has made possible dynamic charge detection, with greater than MHz bandwidth [11-13].

Traditionally radio-frequency electrometry has been performed by aluminium rf-SETs, fabricated using an aluminium double-angle evaporation process. These aluminium rf-SETs are generally operable in the mK

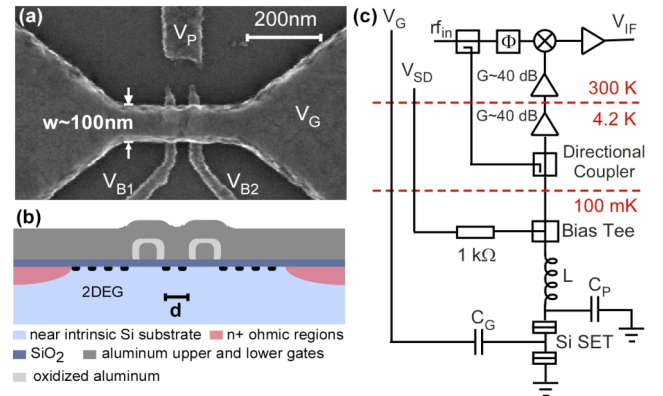


Figure 1. Device structure. (a) Scanning electron micrograph of a typical device. The lower barrier gates, V_{B1} and V_{B2} , are typically $<30\text{nm}$ wide with a separation $d < 40\text{nm}$. The width of the upper MOSFET gate, V_G , of the device reported here was $w = 50\text{nm}$. (b) Schematic cross-section of a device, illustrating the 2DEG induced in the high resistivity silicon by the upper MOSFET gate, and locally depleted by the lower barrier gates. (c) Schematic of the rf measurement set-up. ($L = 470\text{nH}$ and $C_P = 480\text{fF}$)

temperature range due to their small charging energies and also due to the increased charge sensitivity in the superconducting state. Recently the significant achievement of an aluminium rf-SET at 4.2K was reported [14]. Rf reflectometry has also been utilised for fast detection with GaAs point contacts [15-17], and also carbon nanotubes [18].

We report the demonstration at 4.2K of a silicon rf-SET fabricated in a CMOS compatible architecture. This invites new applications of single electron charge detection at liquid helium temperature; for example the integration of the silicon rf-SET into a scanning probe microscope. The tunable tunnel barriers create a flexible device in which it is possible to tune each tunnel barrier as well as the total resistance of the SET, enabling improved matching with the resonant tank circuit. Additionally the architecture presented here is compatible with traditional CMOS technology, suggesting the possibility of integration of these single electron devices on a silicon CMOS chip. Charge sensitivities of better than $10\mu\text{e}/\sqrt{\text{Hz}}$ are demonstrated at MHz bandwidth at mK, and charge sensitivity

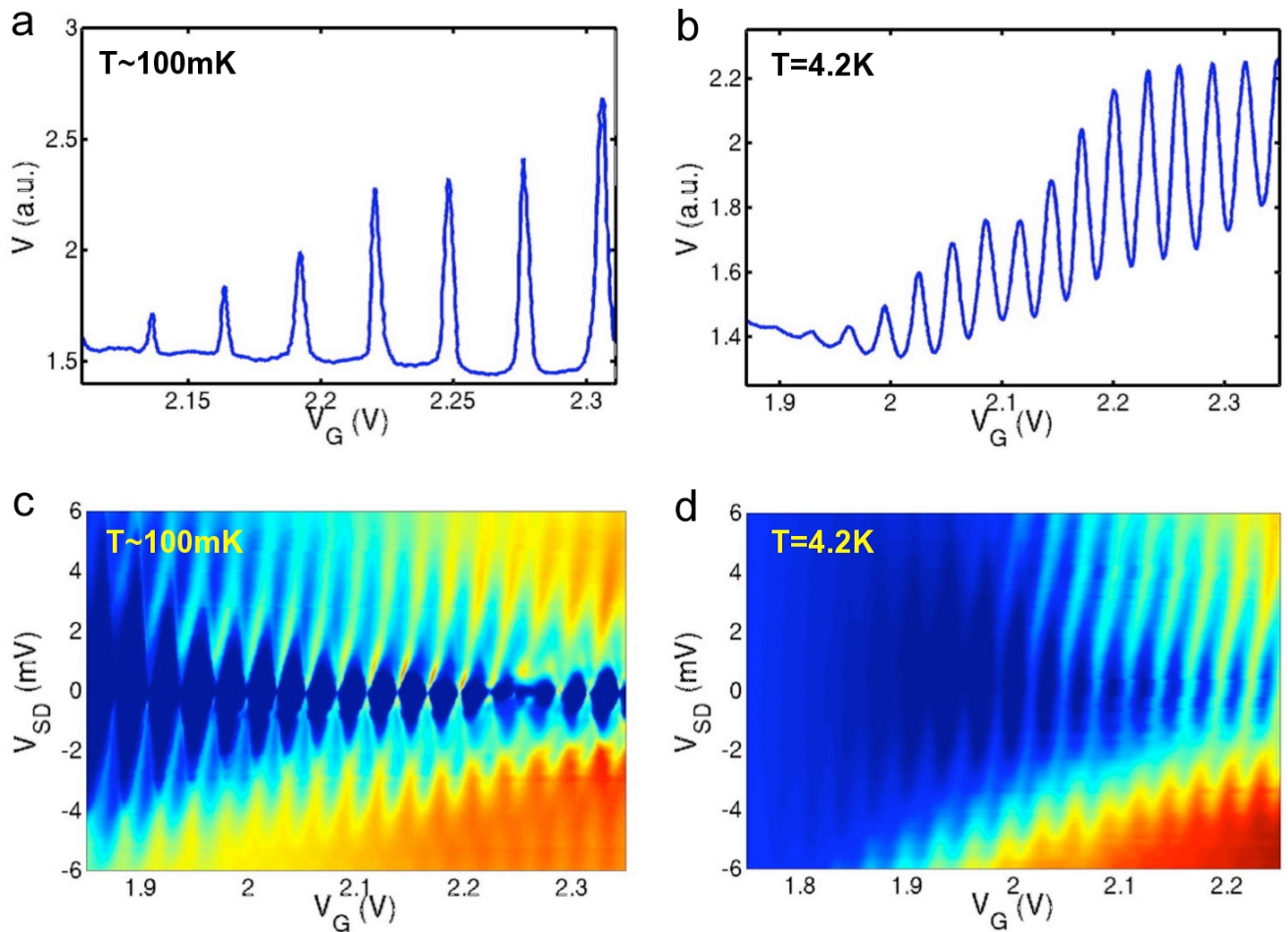


Figure 2. Characteristics of the silicon rf-SET. (a) and (b) Coulomb blockade oscillations at 100mK and 4.2K respectively. (c) and (d) Coulomb diamonds at 100mK and 4.2K respectively. Technical details: (a) and (c) carrier frequency of 334.5 Mhz, carrier power of -88dBm, 32 averages (b) and (d) carrier frequency of 334.5 Mhz, carrier power of -78dBm, 64 averages (a) (b) and (d) $V_{B1}=508\text{mV}$, $V_{B2}=750\text{mV}$, (c) $V_{B1}=508\text{mV}$ and $V_{B2}=750\text{mV}$

of the order $20\mu\text{e}/\sqrt{\text{Hz}}$ is achieved at 4K. These results demonstrate that silicon may be used to fabricate fast, sensitive electrometers for use at 4.2K.

II. EXPERIMENTAL SET-UP

The silicon rf-SET is defined using a double-gated structure on a high resistivity silicon wafer, as shown in Fig. 1. An upper aluminium MOSFET gate induces an electron gas in the silicon substrate. A lower layer of gates is used to locally deplete this induced electron gas in order to form tunnel barriers, thus confining the SET island. The surface of this lower layer of aluminium gates is oxidised, creating an insulating layer of aluminium oxide between the lower and upper gates. This geometry allows the electrostatic creation of small, well-defined dots in silicon. The lower barrier gates are typically less than 30nm wide, separated by a distance, $d < 40\text{nm}$. The width of the upper MOSFET gate of the device reported here was 50nm. This structure has previously been used to investigate silicon quantum dots [7] and has also been used to demonstrate a silicon rf-SET at millikelvin temperature [19]. Further details of the device structure and electrical characteristics can be found in these articles.

Electrical transport measurements were performed in a dilution refrigerator at the base temperature ($\sim 100\text{mK}$) and also at 4.2K. As illustrated in Fig. 1(c), the silicon SET was placed

in an rf tank circuit formed by a surface-mount inductor $L=470\text{nH}$ and the parasitic capacitance, C_p , of the SET to ground. This capacitance was determined to be 480fF based on the observed resonant frequency. A dc source-drain bias was applied using a bias tee and two-terminal dc conductance measurements were performed using a standard low-frequency lock-in technique. An rf carrier signal was applied to the source of the SET at the resonant frequency of the circuit ($\sim 340\text{MHz}$) and the amplified reflected signal was homodyne detected.

III. RESULTS AND DISCUSSION

A network analyzer was used to measure the frequency dependence of the reflected rf signal as a function of gate voltage. The reflected signal is described by the reflection coefficient, $r = |(Z - 50)/(Z + 50)|$ where Z is the impedance of the tank circuit. At the resonant frequency $Z \sim L/(R \times C_p)$, and the reflected rf signal is at a minimum. A shift in the resonant frequency was observed during the turn-on of the device, consistent with measurements of a previous sample [19]. This is explained by an increase in the parasitic capacitance of the SET to ground due to the formation of the induced electron gas.

Periodic Coulomb oscillations are observed at 100mK and at 4.2K, as shown in Fig. 2(a) and (b). Thermal broadening of the oscillations occurs as the temperature is increased. In order

to observe Coulomb blockade it is necessary that the charging energy of the SET is significantly greater than the thermal energy of the system. The charging energy, $E_C=e^2/C_\Sigma$, can be found by performing bias spectroscopy, as shown in Fig. 2(c) and (d). At 100mK the minimum charging energy observed is approximately $E_C=1\text{meV}=11.6\text{K}$. Since this charging energy is significantly greater than the thermal energy at 4.2K, the silicon rf-SET remains operable at this elevated temperature.

The bias spectroscopy reveals a strong dependence of the charging energy on the applied upper MOSFET gate voltage, in agreement with previous dc and rf measurements [7,19]. As the upper MOSFET gate voltage increases the total capacitance also increases, revealed by a decrease of the charging energy. We attribute this increase in capacitance to two effects: firstly an increase in the effective dimensions of the dot and secondly a decrease in the width of the depletion area under the barrier gates.

Measurements of the charge sensitivity of the silicon rf-SET were performed at both 100mK and also at 4.2K. A small sinusoidal signal, with an rms amplitude (q_{rms}) equivalent to ~ 0.01 of an electron on the island was super-imposed onto the dc gate voltage, producing amplitude modulation of the carrier signal. A typical measurement is given in Fig. 3. The charge sensitivity, δq , was then calculated from the resulting signal to noise ratio of the side-bands according to the expression given below

$$\delta q = \frac{\Delta q_{\text{rms}}}{\sqrt{2B} \times 10^{\text{SNR}/20}}, \quad (1)$$

where B is the resolution bandwidth of the spectrum analyzer and SNR is the measured signal to noise ratio. At 100mK the charge sensitivity was found to be $11\mu\text{e}/\sqrt{\text{Hz}}$ at a gate modulation frequency of 1MHz. This is comparable to the sensitivity of $7\mu\text{e}/\sqrt{\text{Hz}}$ of a previous sample obtained after carrier signal optimization [19]. After increasing the temperature to 4.2K the charge sensitivity was found to be $21\mu\text{e}/\sqrt{\text{Hz}}$. The charge sensitivity has decreased, as expected from the thermal broadening of the Coulomb blockade oscillations.

IV. CONCLUSION

In conclusion, we have measured a silicon rf-SET at 4.2K fabricated using tunable tunnel barriers in a silicon MOSFET. Charge sensitivity measurements have been reported, demonstrating sensitivities of approximately $10\mu\text{eV}/\sqrt{\text{Hz}}$ at 100mK and $20\mu\text{eV}/\sqrt{\text{Hz}}$ at 4.2K. This opens up the possibility of fast, sensitive charge detection without the onerous requirement of mK temperature, with the additional benefit of a CMOS compatible structure.

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