Random telegraph signals caused by a single dopant in a metal oxide semiconductor field effect transistor at low temperature

Kouta Ibukuro,1, a) Joseph William Hillier,1 Fayong Liu,1 Muhammad Khaled Husain,1 Zuo Li,1 Isao Tomita,1, 2 Yoshishige Tsuchiya,1 Harvey Nicholas Rutt,1 and Shinichi Saito1, b)

1) School of Electronics and Computer Science, University of Southampton, University Road, Southampton, SO17 1BJ, United Kingdom.
2) Department of Electrical and Computer Engineering, National Institute of Technology, Gifu college. 2236-2 Kaminakawara, Motosu, Gifu, 501-0495, Japan.

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While the importance of atomic-scale features in silicon-based device for quantum application has been recognised and even the placement of a single atom is now feasible, the role of a dopant in the substrate has not attracted much attention in the context of quantum technology. In this paper, we report random telegraph signals (RTSs) originated from trapping and detrapping of an electron at a donor in the substrate of a p-type Metal-Oxide-Semiconductor Field-Effect-Transistor (MOSFET). RTSs, not seen when the substrate was grounded, were observed when a positive bias was applied to the substrate. The comprehensive study on the signals observed reveals that the nature of the RTSs is discrete threshold voltage variations due to the change in depletion layer width depending on the charge state of a single dopant, neutral or positively charged.

I. INTRODUCTION

The importance of atomic-scale features, such as a dopant1–6 and a trap state7–13 has been widely recognised in the context of silicon (Si) quantum technology, such as nano-electronic circuits1–4,14–16 information processing6–9,17–19, hardware security12, bio-sensing13 and metrology.5,10,11,20,21. As the size of Si metal-oxide-semiconductor (MOS) field-effect-transistors (FETs) approaches to the physical limit, electronic circuits based on single-atom devices were proposed14,15. Use of solitary dopants as a fundamental building block of electronic circuits could be a disruptive solution to maintain the rate of device scaling1–4,16,22,23. With regards to quantum information processing, spin qubits based on Si are considered to be promising, due to its weak spin-orbit coupling and abundance of non-magnetic isotopes17–19. Realising spin-qubits with single-implanted donors are interesting, as they can provide a discrete energy level with larger energy separation due to stronger quantum confinement than the one realised by a quantum dot (QD) defined by patterning or field-effect6. Trap states in Si devices have been considered as an impediment to reliable performance of complementary-MOS (CMOS) FETs24–30. However, a few attempts have been made to perform single-spin manipulation based on trap states in a standard MOSFET for spin-qubits, which proved to be successful1–9. Also, the variation caused by trap states can be used as a fingerprint of a device for hardware security12, while a trap state in a liquid-gated FETs for bio-sensing offers enhanced sensitivity to the change in pH of the solution13. Finally, such a trap state is known to be useful for a single-electron pump (SEP)10,11 for quantum metrology20,21. SEP is a periodically driven single-electron transistor with tunable potential barriers, outputting drain current of \( I_d = ef \), where

e is the elementary charge and \( f \) is the frequency at which the device is driven20,21. A SEP that takes advantage of a trap state has achieved 7.4GHz operation with an uncertainty of 20 parts-per-million (ppm)11, approaching the metrological requirement of an electric current standard. Without doubt, engineering of such an atomic-scale structures embedded in a Si device will continue to play a crucial part in future quantum applications.

The first challenge in utilising atomic-scale features is to find their signatures in transport characteristics of the devices.31–34 We recently proposed characterisation of conventional Si MOSFETs with a long integration time at low temperature, which exhibits Coulomb diamonds (CDs)31 and random telegraph signals (RTSs) in current-voltage (I-V) characteristics. RTSs are discrete threshold voltage (\( V_{th} \)) variations over time25,35, and two \( V_{th} \) states are supposed to correspond to an empty and occupied state of a charge trap at Si-SiO2 interface or inside amorphous SiO232. The physical origin of the CDs observed in the MOSFETs were, on the other hand, attributed to remote surface roughness of polycrystalline Si (poly-Si)31. In this sense, single electron phenomena caused by trap states and structural disturbance in standard MOSFETs have been explored. However, towards application envisaging single-atom circuits1–4,16 and spin-qubits6, the use of a single dopant is more desirable and suitable.

In order to achieve single-carrier manipulation using a solitary dopant in a conventional MOSFETs, we focused on the dopants in the substrate, and the dopant ionisation profile was electrically tuned in a systematic manner by applying reverse bias to the substrate. By doing this, we observed RTSs caused by a trapping and detrapping of an electron at a donor in the substrate (well) of a p-type Si MOSFET at low temperatures. The device was initially characterised at 3.8K while the substrate was grounded, and it showed a CD in I-V characteristics, indicating that the effective width of the channel is of the order of 10 nm. Also, no RTSs were observed, which means that no trivial charge traps in the oxide or at the interface were present at this bias condition. However, RTSs started to be

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a) Electronic mail: k1m17@soton.ac.uk
b) Electronic mail: S.Saito@soton.ac.uk
observed by applying positive bias to the substrate, which can be seen as discrete \( V_{th} \) shifts in I-V characteristics. Based on this observation, a physical model to explain this RTS based on trapping and detrapping of an electron at a donor was proposed, where the hole transport was significantly affected by the stochastic change in depletion layer width depending on the charge state of the donor, charge neutral or ionised. The occupancy of the trap level and average lifetimes of two \( I_d \) states were systematically controlled by gate voltage (\( V_g \)), and the dependence of average RTS lifetimes on \( V_g \) suggests that the physical origin of the RTS could be different from trap states at the interface or in the gate oxide\(^{25,36,37} \). The temperature was gradually raised to 25K in order to investigate the dependence of the RTSs on temperature, showing almost no dependence until 16K before the faster RTS switching was observed at higher temperature. This indicates that the trapping and detrapping of an electron is achieved via quantum mechanical tunnelling at low temperature\(^{38} \).

This paper also quantitatively discusses the impact of applying reverse bias to the substrate onto the dopant ionisation profile, based on the result of split capacitance-voltage (C-V) measurements with reverse substrate bias\(^{25,39} \). Application of substrate voltage have been widely used in the context of Si quantum devices\(^{9,10,40} \), though the detailed study on its effect on carrier transport has not been performed. Width of the depletion layer was calculated as a function of \( V_g \) and voltage applied to the well (\( V_{well} \)), and the depletion layer was constantly extended as \( V_{well} \) increased, as expected. Effective hole mobility was also calculated as a function of effective electric field\(^{24,41} \), and the degradation of hole mobility was prominent at low effective electric field, where impurity Coulomb scattering is the dominant scattering mechanism. However, regardless of the values of \( V_{well} \), the hole mobility approaches to the universal mobility curve at higher effective electric field, where Si-SiO\(_2\) interface scattering dominates the mobility degradation\(^{24,41} \). This confirms that the primary effect of applying reverse bias to the substrate is to widen the depletion layer, rather than to increase the electric field across the MOS structure\(^{24,40} \).

II. MOSFET CHARACTERISTIC AT ROOM TEMPERATURE AND LOW TEMPERATURE

A p-type MOSFET fabricated using a standard 65nm technology was characterised at various temperatures (from 300K to 3.8K) with a Janis pulse-tube refrigerator and a Keysight B1500 semiconductor parameter analyser. Figure 1 (a) and (b) show schematics of the cross-sectional and birds-eye views of the device, respectively. The channel length (\( L \)) and width (\( W \)) were 50nm and 10\( \mu \)m, respectively, and the capacitive effective thickness (\( t_{eff} \)) is 2.4nm. The device was mounted on and wire-bonded to a cryogenic sample holder, and the p-type handle layer was insulated from the holder by cryogenic varnish. Electrical contact to the n-type region in the substrate, well, was achieved from the dedicated pad connected to the well (Figure 1 (a)). Phosphorous was used to form the well.

From our previous works\(^{31,32} \), the presence of a QD was expected in our device, resulting in narrower effective channel width than the actual dimension of the device (Figure 1(b)). Figure 1(c) show the transfer characteristics (drain current (\( I_d \)) against gate voltage (\( V_g \))) of the device at both 300K and 3.8K when the drain voltage (\( V_d \)) was -50mV and source was grounded (\( V_s = 0\)mV). At 300K, the subthreshold slope (\( S = \frac{dV_g}{d\log I_d} \)) was 100mV/decade, while off current (\( I_{off} \)) was around -10pA. As the temperature decreased to 3.8K, \( S \) became steeper (14mV/decade) and \( I_{off} \) was less than -10fA, which was the expected behaviour of CMOS transistors at low temperatures\(^{24,31} \). However, if the channel was considered to be uniform in the subthreshold region at 3.8K, \( S \) should have decreased linearly as the temperature decreased, as \( S = \frac{2.3kT}{e} \left( 1 + \frac{C_{dep,m}}{C_{ox}} \right) \), where \( k \) is Boltzmann constant, \( T \) is temperature, \( e \) is elementary charge, \( C_{dep,m} \) is the maximum depletion layer capacitance and \( C_{ox} \) is the oxide capacitance\(^{24} \). This means that the hole channel is considered to be non-uniform and the dominant current path is much narrower than the actual width of the device.

The presence of a QD can be directly verified from 2D contour plots of differential conductance (\( dI_d/dV_g \)) against \( V_s \) and \( V_g \), shown in Figure 2. \( I_d \) was measured twice as a function of \( |V_d| \) (from 0.5V to 0.7V with 1mV increments (forward sweep), and from 0.7V to 0.5V with 1mV decrements (reverse sweep)) with fixed \( V_d \) to check for the absence of hysteresis, and \( V_s \) was varied from -30mV to 30mV with 0.2mV increments. Differential conductance was then calculated and the result for the forward sweep is shown in Figure 2. Compliance value of 1\( \mu \)A was set to limit \( I_d \), which corresponds to two zero conductance region with \( |V_d| = 30\)mV and \( |V_s| = -0.7\)V. Hysteresis was not observed. Several CDs were ob-

![Figure 1](image-url)
erved, which are highlighted by dotted lines in Figure 2. Two CDs with charging energy of about 5meV (CD1 and CD2) were followed by a sequence of CDs with smaller charging energy (CD3), 1 or 2meV, as $|V_g|$ increased. Two CDs with charging energy of 1 or 2meV were also observed at $|V_g| > 0.65V$, which were labelled as CD4 in Figure 2. The presence of CDs, particularly CD1 and CD2, confirms that the dominant transport was through the QD after the transistor turned on. From the charging energy of the dot, the size of the QD can be estimated\textsuperscript{14,31}. The charging energy $(E_c)$ is firstly converted to the coupling capacitance of the QD, $C_S$ by $E_c = e^2 / C_S$, which gives $C_S = 32aF$. $C_S$ can be decomposed into the coupling capacitance of the QD to source (C_S = 15.0aF), drain (C_D = 5.42aF) and gate (C_G = 11.62aF), from the gradient of the CDs\textsuperscript{31,31}. Finally, the size of the QD $(S_{QD})$ can be estimated from $C_G = \epsilon_{eff} \times S_{QD}$ assuming that the $C_{eff}$ is solely determined by the hat, $C_{eff} = \epsilon_{ox} / \epsilon_{eff} = 1.44\mu F/cm^2$. $\epsilon_{ox}$ is permittivity of SiO$_2$ and $\epsilon_0$ is permitivity of vacuum, $8.854 \times 10^{-12} F/m$. $S_{QD}$ is $0.808 \times 10^{-15} m^{-2}$, and the diameter of the QD $(d_{QD} = \sqrt{4S_{QD}/\pi})$ is about 32nm when the shape of the QD is assumed to be rounded\textsuperscript{31}. The origin of the QD can possibly be remote surface roughness due to a poly-Si grain in the gate electrode\textsuperscript{31,32}. The shrinkage of CDs (CD3 and CD4 are smaller than CD1 and CD2) can be attributed to the change in inversion layer thickness\textsuperscript{31}.

FIG. 2. Differential conductance $(dI/dV_g)$ against $V_g$ and $V_d$ at 3.8K. $V_{well}$ was 0V.

These two observations can confirm the transport mechanism in our device at the subthreshold region at low temperature. As $|V_g|$ increased and the device began to operate at the subthreshold region, holes would start to flow through a QD first, since it would provide the current path with low potential energy. After $|V_g|$ exceeded threshold voltage $(V_{th})$, on the other hand, a 2DHG was uniformly formed under the gate dielectric, and the same on current $(I_{on})$ of 0.2mA at 300K was achieved (Figure 1(c)). In the subthreshold region located between those two schemes, the carrier transport is thought to be described as a hybrid of the two mechanisms, where holes were predominantly travelling through a narrow, weak link between source and drain involving the QD, resulting in the standard MOSFET characteristic being modulated by Coulomb blockades from the QD (Figure 2), as well as the gentle sub-threshold swing (Figure 1(c)).

III. EFFECT OF SUBSTRATE BIAS ON DOPING IONISATION PROFILE

In order to investigate how dopants in the substrate affect the hole transport in the channel, positive substrate bias ($V_{well} > 0$) was applied such that the dopant ionisation profile would be systematically changed. Application of positive substrate bias means that the p-n junction between source/drain and the substrate was reversely biased, leading to more dopants becoming ionised and therefore fewer mobile holes being introduced from source/drain at a given $|V_g|$ to satisfy charge neutrality\textsuperscript{24};

$$Q_{tot} = Q_{dep} + Q_{inv}$$ (1)

$$Q_{dep} \rightarrow Q_{dep} = Q_{dep} + \Delta Q_{dep}$$ (2)

$$Q_{inv} \rightarrow Q_{inv} = Q_{inv} - \Delta Q_{inv}$$, (3)

where $Q_{tot}$ is the total charge induced at a certain gate voltage, $Q_{dep}$ is the ionised dopants in the substrate (depletion layer charges), $Q_{inv}$ is the mobile holes introduced from source/drain (inversion layer charges) and $\Delta Q_{dep} (> 0)$ and $\Delta Q_{inv} (> 0)$ are the increase and decrease in $Q_{dep}$ and $Q_{inv}$, respectively, due to the reverse bias being applied to the substrate. This effect is called the “body effect”\textsuperscript{24}, and $|V_{th}|$ was expected to decrease as $V_{well}$ increased, which is equivalent to a positive $|V_{th}|$ shift\textsuperscript{24}.

In order to experimentally obtain $Q_{dep}$ and $Q_{inv}$ as a function of $V_g$ and $V_{well}$, split capacitance-voltage (C-V) measurements with positive substrate bias\textsuperscript{42} were performed. From this split C-V measurements, one can quantitatively estimate how many dopants were additionally ionised by the positive $V_{well}$. This characterisation was performed at room temperature using a Cascade probe station and the B1500. Two devices with $(W/L) = (10\mu m, 10\mu m)$ (device B) and $(10\mu m, 4\mu m)$ (device C) were measured, which were in the same wafer as the one measured at low temperature (device A), such that the extracted parameters from this measurement can be used for the interpretation of the measurement result obtained from device A. The use of two MOSFETs with different gate lengths is known to be helpful to eliminate parasitic capacitance and resistance\textsuperscript{43}. Transfer characteristics with $V_d = -50mV$ were obtained prior to the C-V measurements, and the result from Device B was subtracted from the one from Device C to obtain $I_d$. Figure 3 shows drain conductance $(g_d = I_d/V_d)$ against $V_g$, while $V_{well}$ was varied from 0mV to 500mV with 50mV increments. $V_g$ was swept from 1V to -1V with 1mV decrements, and the results were shown from 0V to -1V in linear scale to highlight the shift in $|V_{ab}|$. $|V_{th}|$ was 0.34V when the substrate was unbiased ($V_{well} = 0V$), and the shift in $|V_{th}|$ towards positive $|V_g|$ was clearly observed as $V_{well}$ increased.

Then, in order to characterise capacitance of the devices, AC signal with a frequency of 100kHz and an amplitude of 100mV was applied on top of $V_g$, which was swept from
with \( V_{\text{well}} = 0 \text{mV} \) in the inversion region.

\( C_{\text{inv}} \) shows its dependence on \( V_{\text{well}} \) in the inversion region (\( V_{th} > V_g \)), corresponding to the threshold voltage shift due to the body effect\(^{(24)} \). At a given \( V_g \), \( C_{\text{inv}} \) is lower when positive \( V_{\text{well}} \) was applied, for example \( V_{\text{well}} = 500 \text{mV} \):

\[
C_{\text{inv}}(V_g, V_{\text{well}} = 0V) > C_{\text{inv}}(V_g, V_{\text{well}} = 500 \text{mV}).
\] (6)

Therefore,

\[
Q_{\text{inv}}(V_g, V_{\text{well}} = 0V) = \int_{V_{FB}}^{V_g} C_{\text{inv}}(V_g, V_{\text{well}} = 0V) dV_g
\] (7)

\[
> \int_{V_{FB}}^{V_g} C_{\text{inv}}(V_g, V_{\text{well}} = 500 \text{mV}) dV_g
\] (8)

\[
= Q_{\text{inv}}(V_g, V_{\text{well}} = 500 \text{mV}).
\] (9)

This result is consistent with the physical picture described in equation (3).

As \( V_{\text{well}} \) increased, accumulation C-V curves are also shifted towards positive \( V_{gs} \), meaning that flatband voltage (\( V_{FB} \)) is shifted by applying positive \( V_{\text{well}} \). This is reasonable, as the flatband condition is determined solely by the difference between \( V_{gs} \) and \( V_{\text{well}} - V_s \), and therefore as \( V_{\text{well}} - V_s \) increased, more \( V_{gs} \) needs to be applied in order to achieve the same flatband condition. This parallel \( V_{FB} \) shift resulted in the increase in maximum depletion layer charge \( Q_{\text{dep,m}} \) (\( Q_{\text{dep}} \) at \( |V_{gs}| \gg |V_{th}| \)) by applying positive \( V_{\text{well}} \), for example 500mV:

\[
Q_{\text{dep,m}}(V_{\text{well}} = 0V) = \int_{V_{FB} = 1.01V}^{V_g} C_{\text{dep}}(V_{gs}, V_{\text{well}} = 0V) dV_{gs}
\] (10)

\[
< \int_{V_{FB} = 1.51V}^{V_g} C_{\text{dep}}(V_{gs}, V_{\text{well}} = 500 \text{mV}) dV_{gs}
\] (11)

\[
= Q_{\text{dep,m}}(V_{\text{well}} = 500 \text{mV}),
\] (12)

which is consistent with equation (2). Table I shows the calculated \( Q_{\text{dep,m}} \) at various \( V_{\text{well}} \) values, which proves the inequality (11).

| \( V_{\text{well}} \) (mV) | 0   | 50  | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 |
|------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| \( Q_{\text{dep,m}} \) (\( \mu C/cm^2 \)) | 0.404 | 0.413 | 0.423 | 0.431 | 0.440 | 0.449 | 0.458 | 0.466 | 0.473 | 0.480 | 0.487 |

So far, from the split C-V measurements, the overall trend expected from body effect (equation (2) and (3)) was experimentally proven. Furthermore, the depletion layer width can be quantitatively obtained as a function of \( V_g \) and \( V_{\text{well}} \). This is equivalent to analyse the ionisation profile of donors in the substrate as \( V_g \) and \( V_{\text{well}} \) changes, which gives further insight into the effect of applying \( V_{\text{well}} \). To this end, the following model was employed\(^{(2)} \):

\[
Q_{\text{dep}}(V_{gs}, V_{\text{well}}) = eN_d W_{\text{dep}}(V_{gs}, V_{\text{well}}),
\] (13)
which is valid when $|V_{gs}| > |V_{FB}|$. This model means that the total amount of $Q_{dep}$ in the n-well per unit area can be described by the product of the substrate doping (donor) concentration ($N_d$) and the depletion layer width ($W_{dep}$). The spatial variation of $N_d$ is ignored in this model and the precise value of $N_d$ is not assumed apriori. Firstly, $N_d$ is determined from $Q_{dep,m}(V_{well} = 0V)$ and maximum depletion layer width, $W_{dep,m}$. After $|V_{gs}|$ exceeds the threshold voltage ($|V_{th}|$), the depletion layer width is expected to be constant, known as maximum depletion layer width\(^\dagger\), which is given below:

$$W_{dep,m} = \frac{4\varepsilon_S k T \ln(N_d/n_i)}{e^2 N_d},$$

(14)

where $\varepsilon_S = 11.9\varepsilon_0$ is permittivity of Si and $n_i$ is intrinsic carrier density of Si, $10^{11}$ cm\(^{-3}\). This $W_{dep,m}$ was assumed to be valid only when $V_{well} = 0V$, and was used as a boundary condition to obtain $N_d$ using $Q_{dep,m}(V_{well} = 0V)$:

$$Q_{dep,m}(V_{well} = 0V) = eN_d \frac{4\varepsilon_S k T \ln(N_d/n_i)}{e^2 N_d},$$

(15)

which gives $N_d = 5.97 \times 10^{17}$ cm\(^{-3}\). This means that the average distance between dopant atoms are 12nm, which is in the same scale as the gate length of the device. Using this $N_d$, $W_{dep}$ was calculated as a function of $V_{gs}$ and $V_{well}$ using equation (13), and plotted in Figure 5. $W_{dep}$ against $V_{gs}$ were plotted by solid lines with a colour gradient from red ($V_{well}$ = 0mV) to purple ($V_{well}$ = 500mV). As expected, $W_{dep}$ becomes almost constant after $|V_{gs}|$ exceeds threshold voltage (-0.34V) at any $V_{well}$. The inset in Figure 5 shows $W_{dep}$ at $V_{gs}$ = -0.5V as a function of $V_{well}$. This shows that in this model the rate of depletion layer widening upon the application of $V_{well}$ ($dW_{dep}/dV_{well}$) is almost constant about 20nm/V.

![Figure 4](image-url) **FIG. 4.** The results of the split C-V measurements with varied $V_{well}$ at 300K. Two insets (a) and (b)) describe the measurement setups to characterise $C_{inv}$ and $C_{dep}$, respectively. $C_{inv}$ against $V_{gs}$ with different $V_{well}$ values (from 0V to 500mV with 50mV increments) are plotted by solid lines with a colour gradient from blue to light green. $C_{dep}$ against $V_{gs}$ with different $V_{well}$ values (from 0V to 500mV with 50mV increments) are plotted by solid lines with a colour gradient from red to purple. Orange empty circles show total capacitance $C_{tot} (= C_{inv} + C_{dep})$ at $V_{well}$ = 0V. A simulated C-V curve using analytical quantum mechanical model was plotted in a black broken line.

![Figure 5](image-url) **FIG. 5.** Depletion layer width ($W_{dep}$) as a function of $V_{gs}$ with varied $V_{well}$ at 300K. (Inset) $W_{dep}$ at $V_{gs}$ = -0.5V as a function of $V_{well}$ (values along the dotted line in the main figure).

By analysing the change in depletion layer width due to application of $V_{well}$, it can be concluded that reverse substrate bias can indeed systematically alter the donor ionisation pro-
file. The increase in ionised dopants in the substrate does not only reduce the minority carriers in the inversion layer, but also enhance interaction between holes and ionised dopants by remote Coulomb scattering, resulting in the reduction of hole mobility. This can be experimentally confirmed by calculating effective hole mobility \( \mu_{\text{eff}} = \frac{1}{\mu_0} \left( \frac{e \mu_{\text{inv}}}{\text{inv}} \right) \) against effective electric field \( E_{\text{eff}} = \frac{1}{\varepsilon_{\text{Si}}} (Q_{\text{den}} + Q_{\text{dep}}) \) at various \( V_{\text{well}} \) values.\(^{11}\) Solid lines with a colour gradient from blue to light green in Figure 6 show the result, and the black dotted line is the universal mobility curve \( (\mu_{\text{inv}} = 185/(1 + E_{\text{eff}}/345)) \) for Si-SiO\(_2\) interface. As can be seen from Figure 6, the degradation of hole mobility is more prominent at low \( E_{\text{eff}} \) values, where the dominant scattering mechanism is remote Coulomb scattering between holes and ionised donors. At high \( E_{\text{eff}} \), however, regardless of \( V_{\text{well}} \) values, all the mobility curves overlapped and approached the universal mobility curve. This means that the scattering at the Si-SiO\(_2\) interface, the dominant scattering mechanism at high \( E_{\text{eff}} \), has not increased much upon the application of \( V_{\text{well}} \), and the enhanced interface scattering does not account much for the degradation of hole mobility. The mobility degradation has been mentioned previously, and the mechanism was considered to be enhanced Si-SiO\(_2\) interface scattering from qualitative discussion.\(^{40,44}\) Our quantitative result reveals that the enhanced Coulomb scattering is the dominant mechanism to explain the mobility reduction by applying \( V_{\text{well}} \).

The reliability of the C-V measurements was assured from good agreement with the numerical simulation based on analytical quantum mechanical model.\(^{45}\) This model assumes the potential exponentially depends on the distance from the Si-SiO\(_2\) interface, which allows one to find an exact solution of the Schrödinger equation. The solution is then feed-backed into Gauss’s law, which determines the parameter of the exponential potential, resulting in self-consistent Poisson-Schrödinger equation.\(^ {45}\) The result of C-V simulation is shown in Figure 4 as a black dashed line, which agreed well with the experimental result with equivalent oxide thickness (EOT) of 2nm being used as a fitting parameter. Other input parameters were \( N_{\text{d}} = 6 \times 10^{17} \text{cm}^{-3} \) and \( V_{\text{FB}} = 1.01 \text{V} \), which were determined from equation (15) and maximum curvature of the C-V curve in accumulation region, respectively. The difference between \( \epsilon_{\text{eff}} = 2.4 \text{nm} \) and EOT = 2nm is attributed to the quantum confinement near the Si-SiO\(_2\) interface, which can be converted into width of wavefunction in Si. \( t_{\text{Si}} = (\epsilon_{\text{eff}} - \text{EOT}) \times \epsilon_{\text{Si}}/\epsilon_{\text{ox}} = 1.2 \text{nm} \), which is reasonable.\(^{31,45,46}\)

**IV. RANDOM TELEGRAPH SIGNALS TRIGGERED BY REVERSE SUBSTRATE BIAS**

After investigating the effect of substrate bias on the dopant ionisation profile in the substrate, detailed I-V scans with positive \( V_{\text{well}} \) were performed to see its effect on the hole transport in the device. Figure 7 (a) to (f) show 2D contour plots of \( I_d \) as a function of \( V_g \) and \( V_d \) at \( V_{\text{well}} = 0 \text{V}, 100 \text{mV}, 200 \text{mV}, 300 \text{mV}, 400 \text{mV} \) and 500mV. \( V_d \) and \( V_g \) were swept from -0.5V to 0.7V and 30mV to -30mV with 1mV and 0.2mV decrements, respectively, and the results within -0.7V < \( V_g < -0.6 \)V and -15mV < \( V_d < 15 \)mV are displayed. Even at current range of sub-\( \mu \)A, the presence of CD4 can be clearly seen. Also, as \( V_{\text{well}} \) increased, \( |V_{\text{gl}}| \) shifted towards higher \( |V_{\text{g}}| \), as expected. Another notable feature in Figure 7 (c) to (e) is that a few discrete current peaks were observed, highlighted by arrows in the figures. Such current peaks were not observed when \( V_{\text{well}} = 0 \text{V} \) (Figure 7 (a)) and the number of current peaks seen in Figure 7 (a) and (f) \( (V_{\text{well}} = 100 \text{mV} \) and 500mV) is much less than Figure 7 (c), (d) and (e) \( (V_{\text{well}} = 200 \text{mV}, 300 \text{mV} \) and 400mV). This indicates that the peaks could only be observed around a certain \( V_{\text{well}} \) value. The current peaks were observed for both positive and negative \( V_g \), and the ones in negative \( V_d \) \( (V_d < 0) \) are addressed in the following discussion. To clarify the nature of the current peaks, \( I_d-V_g \) curves with \( V_{\text{well}} = 200 \text{mV} \) and \( |V_d| \) varying from 7mV to 13mV with 1mV increments are displayed in Figure 8. Forward sweeps (increasing \( |V_g| \) are shown with solid lines, while reverse sweep (decreasing \( |V_g| \)) are shown with dotted lines. Discretised threshold voltage shifts of about 1.5mV were observed around \( |V_{\text{g}}| = 0.65 \text{V} \) in Figure 8, which coincides with the current peaks observed in 2D contour plots. The threshold voltage shifts continued to be observed with higher \( |V_{\text{g}}| \). The inset of Figure 8 shows \( I_d-V_g \) curve with \( V_{\text{well}} = 200 \text{mV} \) and \( |V_d| = 30 \text{mV} \), showing the same threshold voltage shift. To confirm that the observed threshold voltage shift is caused by a single carrier,\(^{47-49}\) \( |I_d| \) was monitored over 1000s (time domain characteristic). The interval of measurements was 100ms, and the integration time (included in the interval) was 20ms. Figure 9 (a) to (e) show the time domain characteristic at various \( |V_{\text{g}}| \) (from large \( |V_{\text{g}}| \) to small \( |V_{\text{g}}| \)), while...
Random telegraph signals caused by...

V. DISCUSSION: SINGLE ELECTRON TRAPPING AND DE-TRAPPING IN THE SUBSTRATE

In the previous sections, the I-V and C-V characteristics of pMOSFETs at room temperature and low temperature were introduced (Section II, III), before unexpected observation of RTSs at 3.8K by the application of positive substrate voltage ($V_{\text{well}}$) were shown in detail (Section IV). The biggest difference from conventional RTSs observed in CMOS devices $^{24-30}$ is that the RTSs were only observed when positive bias was applied to the substrate such that the depletion layer was further widened from its maximum width $^{24,25}$. Although the modification of RTSs parameters, such as $\Delta|I_d|$, lifetime of the two current state ($\tau_{\text{High}}$ and $\tau_{\text{Low}}$), by applying $V_{\text{well}}$ was previously reported $^{25,39}$, RTSs triggered by applying $V_{\text{well}}$ have not been observed so far. As seen in Section III, the primary

![FIG. 7. 2D contour plots of drain current ($I_d$) as a function of $V_g$ and $V_d$ with $V_{\text{well}}$ being (a) 0mV, (b) 100mV, (c) 200mV, (d) 300mV, (e) 400mV and (f) 500mV at 3.8K. Current peaks were highlighted by black arrows in (c), (d) and (e). It took 5s for $V_g$ to be swept from -0.6V to -0.7V.](image)

![FIG. 8. $I_d$ as a function of $V_g$ with $V_{\text{well}}$ = 200mV and varied $V_d$ of (main) -7mV to -13mV with 1mV decrements and (inset) -30mV at 3.8K. Blue solid lines show the results for forwards sweeps ($|V_g|$ increased from 0.62V to 0.66V), while pink broken lines show the results for reverse sweeps ($|V_g|$ decreased from 0.66V to 0.62V). It took 72s for $|V_g|$ to be swept from 0.62V to 0.66V.](image)
effect of applying reverse substrate bias is to increase ionised donors in the substrate and widen the depletion layer, which result in a positive \( |V_{th}| \) shift. Therefore, we attribute the origin of the RTS to a dopant atom ionised by the application of positive \( V_{well} \), capturing and re-emitting an electron and shifting \( |V_{th}| \) accordingly. The presence and absence of a single electron in the substrate and resulting change in the depletion layer width could have a significant impact on the hole transport, as the effective width of the channel was limited by the size of the QD, about 32nm, at low temperature (Figure 1).

Figure 10 illustrates the proposed physical model to explain the mechanism of the RTS. When \( V_{well} \) was grounded (0V), a dopant atom was below the Fermi energy \( (E_F) \) and therefore filled with an electron, meaning that it could not affect the hole transport in the inversion layer (Figure 10 (a)). As \( V_{well} \) increased, the depletion layer extended and the dopant level was subsequently resulted, resulting in the dopant level aligned with \( E_F \) (Figure 10 (b) and (c)). At this condition, both situations where the dopant was ionised or filled with an electron were energetically equally favourable, such that the switching between those two charge states would occur. Further increase in \( V_{well} \) would result in complete ionisation of the dopant, and the dopant could not influence the transport anymore.

![Graph showing time domain characteristics of the random telegraph signals at 3.8K.](image)

In order to justify this model, we estimate how much \( V_{well} \) is required to ionise one dopant under the QD, \( \delta V_{well} \). The extension of depletion layer, \( \delta W_{dep} \), is defined such that the volume under QD \( S_{QD}\delta W_{dep} \) contains one donor. \( S_{QD}\delta W_{dep} N_d = 1 \). This results in \( \delta W_{dep} = 2.1nm \), and therefore \( \delta V_{well} = \delta W_{dep} (dW_{dep}/dV_{well})^{-1} \) is about 0.1V, which is of the same orders of magnitude with \( V_{well} \) causing the RTSs. Considering the uncertainty associated with the size of the QD, this estimation is in good agreement with our observation.

This claim can also be supported from the direction of \( |V_{th}| \) shift due to RTSs. As \( |V_g| \) increased, the dominant current state shifted from the high \( |I_d| \) state to the low \( |I_d| \) state, corresponding to the positive threshold voltage shift (Figure 9). This can be explained by the ionisation of a single dopant due to the increased \( |V_g| \). The dopant was initially well below \( E_F \), before being brought into \( E_F \) by applying positive \( V_{well} \). Then, as \( |V_g| \) increased, the conduction band became bent further and the dopant level became in resonant with \( E_F \), resulting in an electron escaping and re-entering the donor level by quantum mechanical tunnelling or thermal activation. This ionisation contributed to the further widening of the depletion layer, leading to the positive \( |V_{th}| \) shift, consistent with the observation (Figure 9). Further increase in \( |V_g| \) would result in complete ionisation of the dopant, and RTSs would not be observed anymore.

VI. TRAPPING AND DETRAPPING PROCESS OF AN ELECTRON

In the previous section, the physical origin of the RTS was suggested to be a dopant in the substrate, and two current states, high \( |I_d| \) state and low \( |I_d| \) state, were attributed to be high charge states, charge neutral and ionised, respectively. In order to study the mechanism of the RTS further, the statistics of the signal were investigated in detail. Figure 11 shows the occupancy of each of the two current states, which is the probability to observe the high \( |I_d| \) state \( (N_{High}) \) or the low \( |I_d| \) state \( (N_{Low}) \) against gate voltage. \( N_{High} \) and \( N_{Low} \) were defined as follows:

\[
N_{High} = \frac{1}{T} \int_{I_d}^{\infty} P(|I_d|) d|I_d|,
\]

\[
N_{Low} = \frac{1}{T} \int_{-\infty}^{I_d} P(|I_d|) d|I_d|,
\]

where \( P(|I_d|) \) is the probability to observe a certain \( |I_d| \) value (Figure 11). \( \langle I_d \rangle = \frac{1}{2} (I_{d,High} + I_{d,Low}) \) is the average \( |I_d| \) value of the high \( |I_d| \) state \( (I_{d,High}) \) and the low \( |I_d| \) state \( (I_{d,Low}) \), and \( I_T = \int_{-\infty}^{\infty} P(|I_d|) d|I_d| \) is a normalising factor. As \( |V_g| \) increased, \( N_{High} \) decreased and \( N_{Low} \) increased, which is consistent with the transfer characteristic (Figure 8) as well as time domain measurement and their corresponding histograms (Figure 9).

Asymmetry was found in \( N_{High}/|V_g| \) characteristic (Figure 11) around \( |V_g| = 0.645V \). RTSs cannot be detected when \( |V_g| \) was smaller than 0.639V, where the high \( |I_d| \) state dominates (about up to 80%). However, RTSs were still observed when \( |V_g| \) were more than 0.66V, where the dominant low \( |I_d| \) state, exceeded 80%. This asymmetry can be attributed to non-linear \( |I_d| \) - \( |V_g| \) characteristics. Firstly, \( |I_d| \) is only not susceptible to RTSs, but also disturbed by analogue noise such as shot noise, thermal noise, negative bias temperature instabilities (NBTI), noise from electrical component of this systems (cables, adapters etc), which would be overlaid onto the time traces of \( |I_d| \) and widen the probability distribution of \( |I_d| \) around the mean value. For RTSs to be detected, the
FIG. 10. Energy band diagrams to explain the physical model of the random telegraph signals observed in our device. (a) A dopant located at the outside of the maximum depletion layer and lower than Fermi level ($E_F$) could not influence the transport of inversion layer charges, holes in this case. (b) and (c) As $V_{\text{well}}$ increased, the depletion layer extended and the dopant level moved upwards, resulting in the energy level of the dopant aligned with $E_F$. This means that the both charge states of the dopant, occupied by an electron (charge neutral (b)) or unoccupied (ionised (c)), were both energetically equally favourable, and the two states stochastically switched over time. When the dopant became ionised, the depletion layer underneath the hole channel, which is a narrow weak link with the width of 30 nm, was further widened, leading to positive, discrete threshold voltage ($|V_{\text{th}}|$) shift. (d) Further increase in $V_{\text{well}}$ resulted in the complete ionisation of the dopant and the RTS were not observed.

The characteristic of RTS lifetimes ($\tau_{\text{High}}$, time-to-emission and $\tau_{\text{Low}}$, time-to-capture, defined in this paper), particularly its dependence on $V_g$, is considered to reflect the physical origin of the signal\cite{36,37,39}. If the origin of the RTS is a trap in the oxide, the way the average lifetimes ($\langle \tau_{\text{High}} \rangle$ and $\langle \tau_{\text{Low}} \rangle$) depend on $V_g$ is considered to be asymmetric\cite{36,37,39}. This is because the probability for a carrier to be captured by a trap depends both on the carrier density in the inversion layer and $V_g$. $V_g$ determines the energy level of a trap with respect to Fermi energy, and as $V_g$ increases the trap level would become lower and it would be predominantly occupied. In addition, if the carrier density is higher, the chance of a carrier to be captured by a trap would increase further. The emission process, on the other hand, only depends on $V_g$ as there is no other electron to be emitted. This difference in capture and emission process causes the difference in behaviour of time-to-capture and time-to-emission against $V_g$, where time-to-capture strongly depends on $V_g$ while time-to-emission is almost a constant\cite{36,37,39}. Our model is based on a dopant exchanging an electron with n-doped well with fixed density of $N_d$, suggesting that both $\langle \tau_{\text{High}} \rangle$ and $\langle \tau_{\text{Low}} \rangle$ should be modified by $|V_g|$. Therefore, by calculating $\langle \tau_{\text{High}} \rangle$ and $\langle \tau_{\text{Low}} \rangle$ as a function of $V_g$, the observed RTS can be distinguished from the one caused by a trap in the oxide.

As far as the average values of $\langle \tau_{\text{High}} \rangle$ and $\langle \tau_{\text{Low}} \rangle$ are concerned, they can be efficiently obtained from the histogram of time differential of $|I_d|$ ($\delta I_d(t) = |I_d(t+\Delta t)| - |I_d(t)|$), $P(\delta I_d)$\cite{33}:

$$\langle \tau_{\text{High}} \rangle = T_{\text{High}} \int_{-\infty}^{\infty} P(\delta I_d) d\delta I_d$$

$$\langle \tau_{\text{Low}} \rangle = T_{\text{Low}} \int_{-\infty}^{\infty} P(\delta I_d) d\delta I_d$$

where $T_{\text{High}} = N_{\text{High}} T$, $T_{\text{Low}} = N_{\text{Low}} T$, $N_{\text{total}}$ is the total number of measurement points during $T$ and $\delta I_d = \int_{-\infty}^{\infty} P(\delta I_d) d\delta I_d$ is a normalisation factor. The denominator...
The bandwidth of the measurement did not affect the statistics of the RTS. There was no periodicity in this signal and also the finite detection time for individual transitions (from the high \( V_g \) state to low \( V_g \) state) was short enough to capture the RTS with high \( |I_d| \) state and low \( |I_d| \) state, respectively. The distributions of the data points (the solid blue and magenta bars) follow an exponential trend (the red broken line and the green dashed line).

![Figure 11](image1.png)

**FIG. 11.** Occupancy of the two current states (\( N_{\text{High}} \) and \( N_{\text{Low}} \)) against \( V_g \). \( N_{\text{High}} \) and \( N_{\text{Low}} \) at 3.8K were plotted with solid blue square and filled magenta circles, while those at 12K were plotted with triangles with orange lines and diamonds with green lines, respectively. (Inset) Full width of half maximums of the two current states (FWHM\(_{\text{High}}\) and FWHM\(_{\text{Low}}\)) and the amplitude of the random telegraph signals (\( \Delta I/I \)) against \( V_g \) at 3.8K.

Candidate of the physical origin of the observed RTS. In order to further validate this physical model, finally the device was measured at temperatures up to 25K. RTSs were observed at a similar \( |V_g| \) range at higher temperatures as well. The rise in the temperature certainly shifted the threshold voltage, though the statistics of RTS has not been significantly changed, as can be seen from Figure 11. \( N-V_g \) characteristics at 12K are shown in Figure 11, and similar to the case of 3.8K, \( N_{\text{High}}-|V_g| \) and \( N_{\text{Low}}-|V_g| \) curves cross at \( |V_g|=0.645V \), meaning that both states were observed equally frequently at 12K as well. Then, the probability distributions of the individual lifetimes of high \( |I_d| \) state and low \( |I_d| \) state, respectively. The distributions of the data points (the solid blue and magenta bars) follow an exponential trend (the red broken line and the green dashed line).

**FIG. 12.** Study on the lifetime of the RTS observed at 3.8K. (a) Average lifetime of high \( |I_d| \) state and low \( |I_d| \) state (\( \langle \tau_{\text{High}} \rangle \) and \( \langle \tau_{\text{Low}} \rangle \)) against \( V_g \). (b) and (c) Probability distribution of the individual lifetimes of high \( |I_d| \) state and low \( |I_d| \) state, respectively. The distribution of the data points (the solid blue and magenta bars) follows an exponential trend (the red broken line and the green dashed line).

From the analysis on \( \langle \tau_{\text{High}} \rangle \) and \( \langle \tau_{\text{Low}} \rangle \) as a function of \( V_g \), a dopant in the substrate is considered to be a realistic candidate of the physical origin of the observed RTS. In order to further validate this physical model, finally the device was measured at temperatures up to 25K. RTSs were observed at a similar \( |V_g| \) range at higher temperatures as well. The rise in the temperature certainly shifted the threshold voltage, though the statistics of RTS has not been significantly changed, as can be seen from Figure 11. \( N-V_g \) characteristics at 12K are shown in Figure 11, and similar to the case of 3.8K, \( N_{\text{High}}-|V_g| \) and \( N_{\text{Low}}-|V_g| \) curves cross at \( |V_g|=0.645V \), meaning that both states were observed equally frequently at 12K as well. Then, the probability distributions of the individual lifetimes of high \( |I_d| \) state and low \( |I_d| \) state, respectively. The distributions of the data points (the solid blue and magenta bars) follow an exponential trend (the red broken line and the green dashed line).

\[
P_{\text{quantum}} = \tau^{-1} \quad (20)
\]

\[
P_{\text{thermal}} = \tau^{-1} e^{-\frac{A\Delta E}{kT}} \quad (21)
\]

\[
P_{\text{total}} = \tau^{-1} + \tau^{-1} e^{-\frac{A\Delta E}{kT}} \quad (22)
\]

where \( P_{\text{quantum}} \) and \( P_{\text{thermal}} \) are probability for an electron to become trapped or detrapped via quantum mechanical tunnelling at low temperature to thermal activation at higher temperatures.
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FIG. 13. \(\langle \tau_{\text{High}} \rangle\) and \(\langle \tau_{\text{Low}} \rangle\) against the inverse of the temperature, 1000/T, at \(V_g = 0.645\) V. \(\langle \tau_{\text{High}} \rangle\) are plotted with solid blue squares, while \(\langle \tau_{\text{Low}} \rangle\) are plotted with magenta empty circles. The orange dotted line is an Arrhenius plot with an activation energy of 26meV, while the broken green line is the average value of the lifetimes at lower temperature (from 3.8K to 14K). The inset describes the two mechanisms of trapping and detrapping of an electron, quantum mechanical tunnelling and thermal activation, in an energy band diagram.

3.8K is quantum mechanical, indicating that the system in our device can be described by the renowned single impurity Anderson model\(^{55}\). Quantum tunnelling rates can also be associated with the analytic solutions in the case of biased double-well systems\(^{56,57}\).

VII. CONCLUSION

In this paper, observation of random telegraph signals caused by a single dopant in the substrate of a p-type metal-oxide-semiconductor field-effect-transistor was reported. RTSs were initially not observed until the substrate bias was applied such that the depletion layer becomes widened. Trapping and detrapping of an electron changed the depletion layer width under the narrow channel involving a quantum dot, which worked as a sensitive charge sensor. Statistics of individual lifetime of the RTSs obeyed the exponential distribution, and the occupancy of the two current states as well as lifetime were controlled by the gate voltage, as expected. Average lifetimes associated with the discrete current states were modified by gate voltage significantly, indicating that the origin of the signal differs from trap states in the oxide. The temperature dependence of the average lifetime indicates that the tunnelling mechanism transited from quantum mechanical tunnelling to thermal activation as the temperature increased. Engineering of an atomic-scale features and manipulation of a single carrier are crucially important for quantum technology for nano-electronics\(^{1-4,14-16}\), metrology\(^{5,10,11,20,21}\) and even for quantum information processing\(^{6-9,17-19}\). We focused on a dopant in the substrate, and realised single-electron manipulations in an industry-grade Si MOSFET in a reasonably easy manner at a relatively higher temperature of 3.8K. Our work proposes an alternative approach to utilise the existing yet to date little considered candidate of such an atomic-scale feature, a solitary dopant in the substrate, for future quantum application.

CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR CONTRIBUTIONS

K.I, Z.L, M.K.H and S.S prepared samples for measurement. K.I, J.H, F.L, Y.T, H.R and S.S established measurement setup for room temperatures and cryogenic temperatures. K.I, J.H and S.S designed the experiments, and K.I performed measurements. S.S, K.I and I.T proposed the physical model of the observed random telegraph signals. K.I analysed data and drafted manuscript. All authors participated in discussion.
The data that supports the findings of this study are openly available in ePrints Soton, the University of Southampton Institutional Research Repository (https://doi.org/10.5258/SOTON/D1193)\(^8\).

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