Recent work on metal-oxide-silicon (MOS) quantum devices has demonstrated superb control of single electrons in electrostatically defined quantum dots.\cite{1, 2} Silicon structures are a promising platform for the realization of a quantum processor,\cite{3, 4} demonstrating long spin coherence times\cite{5, 6, 7} and a large valley splitting.\cite{8, 9, 10} In addition, silicon enjoys a mature fabrication infrastructure thanks to the complementary MOS industry and is compatible with single ion implantation,\cite{11, 12} allowing for electron-donor coupled qubits.\cite{13, 14} One of the most pressing difficulties in fabricating MOS quantum devices is the presence of disorder at the Si/SiO$_2$ interface.\cite{15} Specifically shallow defects are a few meV below the conduction band edge ($E_C$). These shallow defects are of the same energy scale of a typical electrostatically defined quantum dot potential, and are electrically active at the operating temperatures of a quantum dot device ($\sim 1$ K).\cite{16, 17, 18, 19} In contrast, electrons confined in deeper, mid-gap states are frozen in place and are inert, contributing a static electric field background. As a result, the presence of shallow defects can be catastrophic for single electron control in quantum devices operating at low temperature. These interface traps can inadvertently be introduced during device fabrication by high energy processes, especially from e-beam lithography,\cite{20} the “workhorse” of quantum device fabrication in research labs.\cite{21, 22, 23, 24} While a large body of literature exists on annealing irradiated Si/SiO$_2$ interface defects,\cite{17, 18, 19} most\cite{20} of these measurements are done well above liquid helium temperatures and characterize defects far away from the conduction band edge. Thus, little is known about annealing shallow traps which only manifest themselves at low temperatures.

We have fabricated devices with the highest reported electron mobility for a MOSFET with an oxide thickness of 30 nm or thinner\cite{20} ($23,000 \text{ cm}^2/\text{Vs}$) and subjected these devices to e-beam irradiation and a subsequent forming gas anneal. Using electron spin resonance (ESR)\cite{21, 22} we directly measure the shallow trap density of our devices and compare these results to more typical measurements of the Si/SiO$_2$ interface, namely, low temperature transport measurements of electron mobility\cite{8, 16, 20} and percolation thresholds.\cite{23} Measurements of electron mobility are a commonly used method of assessing the oxide interface in MOS devices but provide only indirect measurements of confined shallow traps.\cite{21} Our transport data show that the e-beam dose significantly degrades a device’s peak mobility, but a forming gas anneal can restore its peak mobility to within a factor of two of the unexposed sample’s. Despite this difference in peak mobility, our devices display very similar T=0 percolation threshold densities. Our ESR measurements of the density of shallow traps demonstrate that a forming gas anneal effectively removes shallow traps generated in the e-beam exposed sample over the entire measured energy range of approximately 4 meV (4.2 K) to 0.3 meV (360 mK) below the conduction band edge. We find our devices’ lowest temperature ESR measurement of shallow traps match the T=0 percolation threshold density, demonstrating agreement between two independent methods of assessing the oxide interface.

The devices measured in this work are n-channel inversion MOSFETs fabricated at Princeton from a commercially grown (Novati Technologies) gate stack. Our starting substrate consists of a high resistivity (1000-3000 $\Omega$-cm) float zone p-type (100) silicon wafer with 30 nm of dry, chlorinated thermal oxide and capped with 200 nm of un-doped amorphous silicon (a-Si). For both sets of devices, large-area MOSFETs ($3.3 \times 20 \text{ mm}^2$) were
fabricated for ESR measurements and Hall bars (0.2 × 4 mm²) were fabricated for transport measurements. A large gate area (~1 cm²) is necessary to detect the spin signal of 2D electrons at 4.2 K using X-band ESR. Holes were etched through the a-Si for self-aligned ohmic contacts using an SF₆ and C₄F₈ based plasma and the underlying oxide was etched with buffered HF. The devices were implanted with As (35 keV, 5 × 10¹⁵ cm⁻², Leonard Kroko, Inc.) to dope the source/drain contacts for soldering to the device. In addition to the two sets of devices mentioned above, a third Hall bar (sample C) was fabricated to demonstrate the damage created by the e-beam exposure. This sample was fabricated identically to sample A but was then coated with e-beam resist and received an e-beam exposure (identical to sample B) at the very end of processing, with no post-exposure anneal.

Transport measurements were done on all three sets of devices using standard low frequency lock-in techniques. Samples A and B were measured in a 3He cryostat (Janis Research) at temperatures between 335 mK and 4.5 K using a constant excitation current of 1.5 nA. The threshold voltage (Vth) of these two devices was measured to be ≈ 0.07 V at 4.2 K and increases slightly with decreasing temperature to ≈ 0.2 V at 335 mK. Sample C was measured at 4.2 K with an excitation current of 115 nA and its threshold voltage was measured to be 1.2 V, indicating approximately 10¹² cm⁻² net oxide charges (interface states and fixed oxide charge) created by the e-beam exposure. For each sample, electron densities (n) were calibrated by measuring the Hall resistivity in a 0.5 T field and the mobility was extracted by standard four-terminal lock-in measurements of the sample resistivity. Mobility (μ) data are summarized in Figure 1 which shows a peak mobility for sample A of 23,000 cm²/Vs at n = 6.3 × 10¹¹ cm⁻², 14,000 cm²/Vs at n = 6.1 × 10¹² cm⁻² for sample B, and < 1,000 cm²/Vs at n = 5.4 × 10¹² cm⁻² for sample C. Sample A demonstrates the highest reported electron mobility for a MOSFET with an oxide thickness of 30 nm or thinner. Comparing the mobility data for all three devices show that the e-beam dose signifi-
cantly degrades the oxide interface (sample C) and that a forming gas anneal is sufficient to restore an e-beamed device to high mobility (sample B).

Peak mobility, however, is measured at relatively high electron densities where the two dimensional electron gas (2DEG) can effectively screen out scattering centers and as such is not necessarily a useful indicator of the oxide interface quality for quantum devices operating in the few electron regime. An alternative method used to assess the interface quality from transport measurements is to fit the measured conductivity (\(\sigma\)) to a percolation transition model of the form \(\sigma(n) = A(n - n_p)^2\), and extract the percolation threshold density \((n_p)\). \(n_p\) gives a measure of the minimum number of carriers required to fill the disorder landscape before a conducting pathway can be supported. Holding the critical percolation exponent \(p\) at 1.31, the expected value for a 2D system, and fixing the pre-factor \(A\) to the best-fit value obtained for each device at the lowest temperature measured, we extract a value of \(n_p\) at each measured temperature (Fig. 2). Using the functional form \(n_p = n_0 + Ce^{-b/T}\), we can extrapolate the percolation threshold to zero temperature and extract \(n_0\), the T=0 percolation threshold density. The exponential term \(b\) is an energy gap related to the impurity distribution of the system. Our fit yields \(n_p = 0.85 + 1.46e^{-2.25/T}\) for sample A and \(n_p = 0.95 + 0.88e^{-3.00/T}\) for sample B, showing very similar T=0 percolation thresholds of 0.83 \(\times\) 10\(^{11}\) cm\(^{-2}\) and 0.95 \(\times\) 10\(^{11}\) cm\(^{-2}\), respectively.

Using ESR we can directly measure the density of electrons confined in shallow traps in samples A and B. We use X-band (\(\sim\) 9.6 GHz, \(\sim\) 3400 G) continuous wave ESR to measure the intensity of the 2DEG spin signal as a function of gate voltage \((V_G)\) at fixed temperature between 360 mK and 4.2 K. Figure 3 shows an example of the number of unpaired spins, calculated as the double integral of the ESR spectrum, as a function of \(V_G\). The data shown in Figure 3 is from sample B, measured at 1.50 K. As \(V_G\) is scanned below threshold, the ESR signal decreases as shallow traps in the channel are thermally depopulated. At some \(V_G\), the signal saturates ("dark" curve in Fig. 3) when the chemical potential is equal to the Fermi level. Illuminating the sample with above band gap (1050 nm) light relaxes the system by neutralizing confined electrons with holes and the corresponding ("post-LED") ESR signal decreases and eventually goes to zero at voltage \(V^0\).

With values for \(V^*\) and \(V^0\), we may then calculate the number of electrons confined in shallow traps \((n_{conf})\) at each measured temperature using the relation \(\epsilon \cdot n_{conf} = C_{ox}(V^* - V^0)\), where \(C_{ox}\) is the oxide capacitance measured from the Hall resistivity. The energy scale of the shallowest populated traps at each temperature is approximately 10\(k_B\cdot T\). Figure 3 summarizes these data for samples A and B and plots data from a previous study for reference. We note that the samples studied in the current work demonstrate similar densities of shallow traps to the previously studied Sandia device. As temperature decreases, the density of confined charge increases as more electrons are frozen into shallower traps. Within experimental error, samples A and B demonstrate the same density of shallow traps across the measured temperature range, \(\approx 9 \times 10^{10}\) cm\(^{-2}\) at \(\geq 0.3\) meV below \(E_C\) (360 mK) and \(\approx 3 \times 10^{10}\) cm\(^{-2}\) at \(\geq 2\) meV below \(E_C\) (2.0 K). This measurement is
consistent with the $T=0$ percolation threshold densities for both devices studied ($n_{\text{T}0}^{A,B}$), also plotted in figure 4 and demonstrates the efficacy of the forming gas anneal for removing e-beam generated shallow defects across the measured energy range.

In summary, we have fabricated and measured high-mobility MOSFETs and have shown that a forming gas anneal is sufficient to restore an e-beam irradiated sample to the quality of an un-irradiated sample, as measured by the the extraction of a $T=0$ percolation threshold and ESR measurements of the density of shallow traps. We believe that these measurements, as opposed to peak mobility, are more relevant metrics to characterize MOS interfaces for quantum devices operating in the low electron density regime and show that the two separate measurements agree with each other at the lowest measured temperature.

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