The Effect of Electrostatic Screening on a Nanometer Scale Electrometer

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Abstract

We investigate the effect of electrostatic screening on a nanoscale silicon MOSFET electrometer. We find that screening by the lightly doped *p*-type substrate, on which the MOSFET is fabricated, significantly affects the sensitivity of the device. We are able to tune the rate and magnitude of the screening effect by varying the temperature and the voltages applied to the device, respectively. We show that despite this screening effect, the electrometer is still very sensitive to its electrostatic environment, even at room temperature.

Keywords: Nanoscale electrometer, electrostatic screening, charge transport, thin film

Nanoscale electrometers have emerged as powerful tools for studying a wide variety of solid state systems. These sensors can be integrated on a semiconductor chip adjacent to a solid state structure of interest,[1] or mounted on a scanning probe tip.[2] Utilized in these configurations, nanoscale electrometers have had a great impact on the study of single electron devices,[3–7] disordered materials,[8,9] and high mobility two dimensional electron gases.[10,11] The small size of these electrometers can lead to high charge sensitivities,[12] which are central to many of these applications. It is widely recognized that, of the many factors that may limit the sensitivity of a nanoscale

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electrometer, electrostatic screening is likely to be one of the most important. However, because in most cases the effect of the screening is more or less fixed, and cannot be easily tuned, there have been few if any experimental investigations of this effect.

In this Letter, we characterize the effect of electrostatic screening on the sensitivity of a nanoscale MOSFET (metal-oxide-silicon field-effect-transistor) electrometer. For our device, we find that screening by the lightly doped *p*-type silicon substrate, on which the MOSFET is fabricated, significantly affects the charge sensitivity of the device. However, because this screening is caused by a lightly doped semiconductor as opposed to a metal, we are able to tune both the rate and the magnitude of the screening effect *in situ* by varying the temperature and depth of the depletion region in the substrate, respectively. This tunability allows us to quantify the effect of screening for our system. We demonstrate that, despite the effects of electrostatic screening, our nanoscale electrometer can still detect very small charge fluctuations, even at room temperature.

The device used in these experiments has been discussed previously,[9] and consists of a nanometer scale silicon MOSFET that is electrostatically coupled to a strip of hydrogenated amorphous silicon (a-Si:H). An electron micrograph of the device is shown in Figure 1(a). The *n*-channel MOSFET is fabricated using standard CMOS techniques on a silicon substrate. The substrate is lightly doped *p*-type with boron ($N_B \approx 3 \times 10^{15}$ cm^{-3}). Adjacent to the gate of the MOSFET, we nanopattern a strip of phosphorous doped a-Si:H. We make electrical contact to the a-Si:H using two gold contacts, which are visible as the bright regions in the two lower corners of the electron micrograph in Figure 1(a). For all of the work discussed here, a positive voltage is applied to the gate of the MOSFET, so that an inversion layer forms at the Si-SiO_2 interface beneath the gate, as shown in Figure 1(b). The conductance of the MOSFET inversion layer, G_M, is limited by its narrowest portion, which is located underneath the $\approx$ 60 nm wide constriction in the gate. Electrical contact is made to the inversion layer through two degenerately doped *n*-type silicon regions located on either side of the constriction (not shown in the micrograph). We measure G_M by applying a small voltage $\sim$ 5 mV to one contact, and measuring the current that flows out through the other. We make electrical contact to the *p*-type substrate through the back of the chip. For the data reported below, we negatively bias the p-type substrate by V_{sub} = -3 V relative to the n-type contacts unless otherwise indicated.

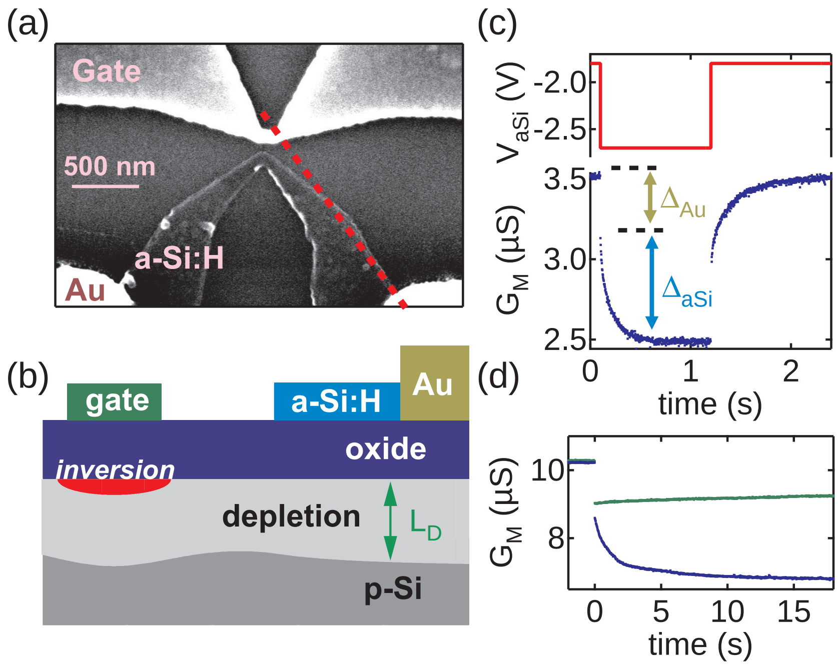

Figure 1: (a) Electron micrograph of MOSFET gate , a-Si:H strip, and gold contacts. (b) Sketch of the cross-section of the device along the dashed red line in (a). When a positive voltage is applied to the gate, an inversion layer forms at the Si-SiO_2 interface. A depletion region forms in the p-type silicon substrate beneath the Si-SiO_2 interface, as discussed in the main text. The depth of the depletion region below the Si-SiO_2 interface is denoted L_D. (c) Voltage sequence applied to one of the gold contacts (top trace) and the conductance of the MOSFET in response to changes in charge on the gold (Δ_{Au}) and a-Si:H (Δ_{aSi}) (bottom trace), at T = 125 K, as discussed in the main text. (d) Result of stepping the voltage applied to the gold contacts at T = 79 K for a device in which the strip of a-Si:H is connected to only one of the two gold contacts, as discussed in the main text. For the blue (green) data the gold contact connected (not connected) to the a-Si:H strip is changed. For these data V_{sub} = 0 V.

The conductance of the MOSFET is extremely sensitive to its electrostatic environment. In particular, G_M is sensitive to changes in charge in either the a-Si:H or the gold contacts. As we show below, this sensitivity is significantly affected by screening by the p-type silicon substrate: If charge Q is added to the a-Si:H or gold contacts, an oppositely charged region will form in the substrate underneath, thereby reducing the effect of Q on G_M. This screening charge is located at the Si-SiO_2 interface, or, if the silicon beneath the Si-SiO_2 interface is depleted of holes (Figure 1(b)), the screening charge will be located a distance L_D beneath the Si-SiO_2 interface.

Our measurement consists of stepping the voltage V_{aSi} applied to one of the a-Si:H gold contacts while simultaneously monitoring G_M. An example is shown in Figure 1(c). Here we set the voltage applied to one gold contact to 0 V, and apply the voltage sequence shown in the top trace of Figure 1(c) to the other contact.[13] The bottom trace of Figure 1(c) shows the variation in G_M in response to the voltage sequence. When V_{aSi} is first stepped from -1.8 V to -2.7 V, G_M quickly drops by an amount Δ_{Au},[14] and then decreases slowly by an amount Δ_{aSi}.

As we have demonstrated in MacLean *et al.*,[9] the slow change Δ_{aSi} in G_M is caused by the slow addition of negative charge to the a-Si:H. The MOSFET electrometer senses this change in charge electrostatically, and G_M decreases as negative charge is added to the a-Si:H. The time scale of this charging is a direct measurement of the resistance of the a-Si:H strip.[9] The much more rapid drop Δ_{Au} in G_M is caused by the negative charge added to the gold contacts, which charge up very quickly because of their low electrical resistance. When V_{aSi} is returned to -1.8 V, the same responses Δ_{Au} and Δ_{aSi} are observed but with the opposite sign, as negative charge is now removed from the gold and the a-Si:H. A similar response is observed when the voltage sequence is applied to the other gold contact, or to both contacts at the same time.

To confirm that our interpretation of the data is correct, we study a separate device where, like the device shown in Figure 1(a), a strip of a-Si:H is patterned adjacent to a nanoscale MOSFET. However, for this device, the strip of a-Si:H is connected to only one of the two gold contacts. The data is shown in Figure 1(d). At $t = 0$ we step one contact from 0 to -9.9 V, while the other contact is held constant at 0 V. A rapid drop Δ_{Au} is observed when the pulse is applied to either one of the gold contacts, but the slower response Δ_{aSi} is only observed when the pulse is applied to the gold which is connected to the strip of a-Si:H, confirming our interpretation of the data.

The sensitivity of G_M to its electrostatic environment depends on screening by the underlying *p*-type silicon substrate. To demonstrate this, we examine the response of the MOSFET to changes in charge in the gold contacts at a temperature $T \approx 10$ K, lower than the temperature at which the data shown in Figure 1 are acquired. At this temperature, the a-Si:H is so resistive that it does

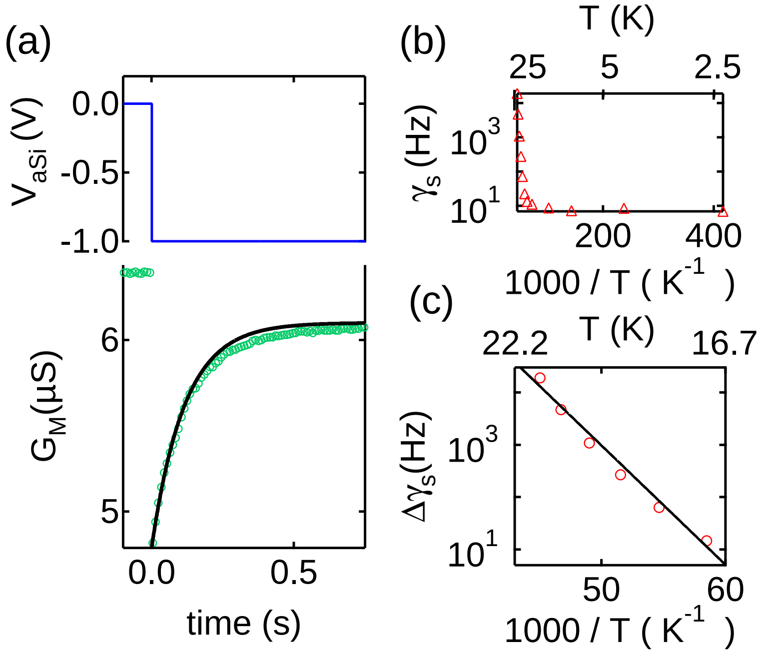

Figure 2: (a) Observation of the screening effect at T = 9.8 K, as discussed in the main text. The top trace shows the voltage step applied to the a-Si:H gold contact. For the lower trace, the solid black curve is a fit to an exponential, as discussed in the main text. (b) Screening rate γ_s as a function of inverse temperature. (c) Change in screening rate $\Delta\gamma_s$ as a function of inverse temperature, as described in the main text. The solid line is a theoretical fit described in the main text. For all of these data, $V_{sub} = 0$.

not charge up on the time scale of the experiment,[9] so that we can add charge to the a-Si:H gold contacts but not to the a-Si:H itself. The results are shown in Figure 2(a). When we change the voltage applied to the a-Si:H gold contacts from 0 to -1 V (top trace), we see a large decrease in the MOSFET conductance, which gradually dies away as time progresses (bottom trace).

The gradual dying away of the decrease in G_M can be understood in terms of screening. When we add charge to the gold contact, an opposing charge in the *p*-type substrate is induced, reducing the overall effect on G_M. At low temperatures, the resistance of the substrate is high, and this charge is induced at a slow rate. To quantify this rate, we fit the G_M trace to an exponential $G_M(t) = G_\infty + G_{scr}e^{-\gamma_s t}$, where G_∞ and G_{scr} are constants that depend on the voltages applied to the MOSFET gate, *p*-type substrate, and gold electrodes, and γ_s is the screening rate.

To show that this screening effect is caused by the *p*-type silicon substrate, we measure γ_s as a function of temperature. The results are shown in Figure 2(b). As the temperature is reduced, γ_s drops, saturating at a minimum value $\gamma_{min} \approx 8$ Hz. In Figure 2(c), we plot $\Delta\gamma_s = \gamma_s$ - γ_{min} as a function of inverse temperature, and fit to an activated temperature dependence $\Delta\gamma_s \propto e^{-E_A/kT}$. We obtain E_A = 45 $\pm$ 5 meV, which agrees well with the boron acceptor binding energy.[15] For boron-doped silicon with no donor compensation, the Fermi level lies between the valence band and the boron donor level, and the activation energy for hole transport is therefore half of the boron acceptor binding energy. However, at sufficiently low temperatures, a small concentration of compensating donor states caused by defects or impurities N_D will move the Fermi level into the acceptor band.[16] In our case, the number of defects required is only $N_D \sim 10^{10}$ cm^{-3}. Because the required density is so small, we expect the Fermi level to lie in the acceptor band, and the activation energy required for the generation of holes in the valence band to be the boron acceptor binding energy. The correspondence between the activation energy for the screening and the boron acceptor binding energy demonstrates that the conductivity of the boron doped substrate limits γ_s. Presumably γ_s saturates at a minimum value γ_{min} because some conduction mechanism other than activation of holes in the *p*-type substrate dominates at low temperature. It is possible that this low temperature conduction occurs via tunneling of electrons between acceptor states[16] in the *p*-type substrate. In any case, from this data it is clear that screening by holes in the boron doped substrate significantly reduces the sensitivity of the MOSFET.

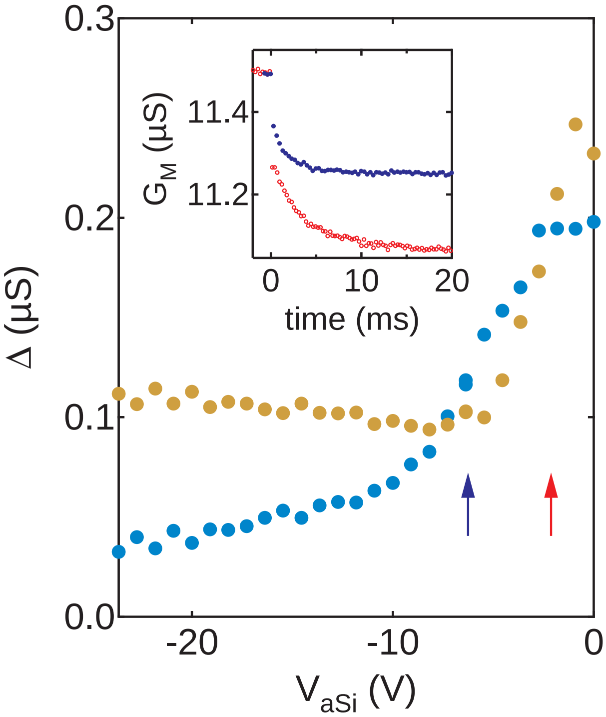

Figure 3: Δ_{aSi} (blue circles) and Δ_{Au} (gold circles) measured as a function of V_{aSi} at T = 139 K, as discussed in the main text. For these data, we make the MOSFET gate voltage more positive as V_{aSi} is made more negative so that $G_M \approx 11$ μS at the start of each $G_M(t)$ trace. (Inset) Examples of data from which Δ_{aSi} and Δ_{Au} are extracted for two different V_{aSi} values. For both $G_M(t)$ traces, V_{aSi} is stepped by -0.5 V at $t = 0$. The data are offset vertically by a small amount for clarity. The blue and red data sets are taken at the positions of the blue and red arrows, respectively. The decrease in both Δ_{aSi} and Δ_{Au} with increasingly negative V_{aSi} is clearly visible.

At higher temperatures $T > 25$ K, γ_s becomes too fast for us to measure. In this regime, we investigate the dependence of Δ_{aSi} and Δ_{Au} on V_{aSi}. The results are shown in Figure 3. Here we step the voltage applied to both gold contacts from V_{aSi} to $V_{aSi} - \Delta V$, where ΔV = 0.5 V. We extract Δ_{aSi} and Δ_{Au} from the resulting $G_M(t)$ trace as depicted in Figure 1(c). We measure both Δ_{aSi} and Δ_{Au} as a function of V_{aSi} and find that both of these quantities decrease as V_{aSi} is made more negative. The decreases in Δ_{aSi} and Δ_{Au} are clearly visible when the $G_M(t)$ traces taken at different V_{aSi} values are compared, as is shown in the inset to Figure 3.

These results can be understood in terms of screening by the p-type substrate in the following way: At V_{aSi} = 0 V, the p-type substrate beneath the Si-SiO_2 is depleted, as depicted in Figure 1(a). As V_{aSi} is made more negative, L_D is reduced beneath the gold and the a-Si:H. This has the effect of making the screening more effective, because it brings the holes in the substrate closer to the charge they are screening. As a result, both Δ_{Au} and Δ_{aSi} decrease as V_{aSi} is made more negative.[17]

The response of G_M to the gold Δ_{Au} decreases as V_{aSi} is made more negative until $V_{aSi} \approx$ -8 V, at which point it saturates. This saturation is expected, because once the depletion layer below the gold shrinks to zero, so that the Si-SiO_2 interface underneath the gold is in accumulation, the distance between the charge on the gold and the screening charge is fixed at the SiO_2 thickness (100 nm). Δ_{aSi} does not appear to saturate as V_{aSi} is made more negative. This is not surprising, because the a-Si:H is very close to the MOSFET gate. Because there must always be a depletion layer between the inversion layer of the MOSFET and the p-type substrate, the Si-SiO_2 interface underneath the a-Si:H cannot be brought into accumulation, and the signal does not saturate. It is however surprising that for $V_{aSi} <$ -10 V, Δ_{Au} is larger than Δ_{aSi}. Although the gold contacts are physically much larger than the a-Si:H strip, which enhances their effect on G_M relative to the a-Si:H, the a-Si:H strip is much closer to the MOSFET, so one would not expect Δ_{Au} ever to be significantly larger than Δ_{aSi}. Thus, although the dependencies of Δ_{aSi} and Δ_{Au} on V_{aSi} can be understood in terms of screening, the relative magnitudes of these quantities are not currently understood. We have also measured the dependence of Δ_{Au} and Δ_{aSi} on V_{aSi} at T = 98 K and T = 179 K. The results are qualitatively similar, but the relative magnitudes of Δ_{aSi} and Δ_{Au} change somewhat depending on the temperature, a result that is also currently not understood.

We have thus seen that screening by holes in the p-type substrate decreases the sensitivity of our MOSFET electrometer. We expect that there are other sources of screening in our system, for instance by the metallic gate of the MOSFET. Despite the effect of screening, our electrometer is still sensitive to very small charge fluctuations in the a-Si:H, even at room temperature. An intriguing demonstration of this is the sensitivity of the MOSFET to telegraph noise switches in the a-Si:H. $1/f$ noise and discrete telegraph switches have been observed previously in the resistance of macroscopic a-Si:H samples.[18] The discrete switching that is sometimes observed occurs for

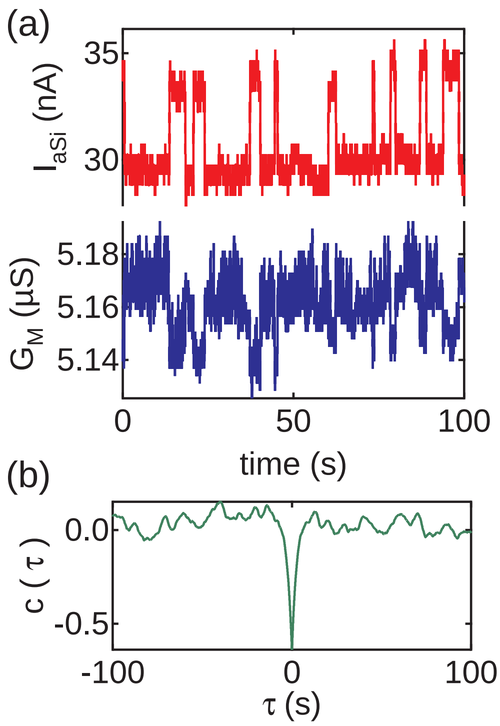

Figure 4: Noise correlations measured at room temperature. (a) Current through a-Si:H strip I_{aSi} (top trace) and transistor conductance G_M (bottom trace) as a function of time. Here we apply a constant voltage bias of 2 V across the a-Si:H strip. (c) Correlation between I_{aSi} and G_M, as discussed in the main text.

samples where the conductance is dominated by filaments small enough to be affected by a single switch. While the microscopic origin of $1/f$ noise in a-Si:H is unclear, its phenomenology is quite rich, and it is closely connected with Staebler-Wronski effect,[19] as demonstrated in Parman *et al.*[20]

At room temperature, where the resistance of the a-Si:H is not too large, we apply a voltage between the two gold a-Si:H contacts and measure the current I_{aSi} that flows through the a-Si:H strip. The top trace of Figure 4(a) shows I_{aSi} measured as a function of time, exhibiting clear telegraph noise. This switching appeared and disappeared apparently randomly, lasting $\sim$ 1 day. Because our sample is nanopatterned, it is not clear whether the origin of the telegraph noise we observe is the same as the origin of the noise found in bulk a-Si:H samples. However, the conductance of our heavily doped a-Si:H strip is only weakly dependent on the voltages of nearby gates, such as the voltage applied to the MOSFET gate or *p*-type substrate. For example, we find that we must change the MOSFET gate voltage by $\sim$ 30 V in order to produce a change in I_{aSi} as large as the $\sim$ 5 pA fluctuations shown in Figure 4(a). The narrow a-Si:H strip is thus not very sensitive to its electrostatic environment, and it is therefore likely that the switching seen in Figure 4(a) results from fluctuations inside or on the surface of the a-Si:H, as opposed to electron trapping external to the a-Si:H.

As we measure I_{aSi}(t), we simultaneously measure G_M(t), and the results are plotted in the bottom trace of Figure 4(a). We see that I_{aSi} and G_M are anti-correlated. When I_{aSi} jumps up, G_M jumps down, and vice versa. This anti-correlation is demonstrated quantitatively in Figure 4(b). Here we measure I_{aSi} and G_M simultaneously for a much longer time than shown in Figure 4(a), and compute the cross-correlation function between the two signals $c(\tau)$.[21] Here we have normalized $c(\tau)$ by subtracting the product of the means of I_{aSi} and G_M, and then dividing by the product of their standard deviations.[22] We see that for our data $c(\tau)$ has a negative peak at $\tau = 0$ with a value ≈ -0.6, indicating that the two signals I_{aSi} and G_M are highly anti-correlated: With our normalization $c(0) = -1$ corresponds to perfect anti-correlation.

From these data, it is clear that the MOSFET electrometer can detect single switches in a material adjacent to it. It may be that electrostatic fluctuations that give rise to the switching noise in the a-Si:H current are detected by the MOSFET directly, or that these fluctuations change the charge distribution along the a-Si:H strip to which the MOSFET is extremely sensitive. We have observed telegraph noise in the current through nanopatterned strips of a-Si:H other than the one studied here, but these samples were not fabricated adjacent to a MOSFET charge sensor. The intermittency of the switch investigated here made it difficult to study in detail, and more work is required to determine the mechanism by which the MOSFET senses these switches.

We can quantify the sensitivity of our MOSFET charge sensor from the data shown in Figure 3.[23] From the size of the V_{aSi} step (0.5 V), $\Delta_{aSi} \sim 0.1\ \mu$S, and the capacitance of the a-Si:H strip (C $\sim$ 100 aF), we estimate that the addition of a single electron charge distributed uniformly along the a-Si:H strip produces a change in G_M of order 0.1 nS. However, since the sensitivity of the MOSFET depends on r, the distance between the electron charge and the MOSFET, we expect that a single charge added to the portion of the strip closest to the MOSFET would produce a considerably larger change in G_M. A charge Q added to the strip is screened by an equal and opposite charge -Q in the substrate. The potential produced by this pair of charges is that of a dipole, and falls off as $1/r^2$ for large r. The central portion of the a-Si:H strip is only $\sim$ 60 nm from the MOSFET, whereas most of the rest of the strip is 10 times farther away. Therefore, G_M could change by $\sim 10^2 \times$ 0.1 nS = 10 nS for a single charge added to the central portion of the a-Si:H strip. Further work simulating these effects is required to calculate the exact dependence of the sensitivity of the MOSFET on r, and to more quantitatively characterize the MOSFET sensitivity.

In summary, we have shown experimentally that electrostatic screening significantly affects the charge sensitivity of a nanometer scale electrometer and that despite this effect, the electrometer is still very sensitive to its electrostatic environment, even at room temperature. We expect that this work will be used to help mitigate the effects of screening in the development of even more sensitive nanoscale electrometers.

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[23] We do not have a direct measurement of the absolute bandwidth of the MOSFET sensor. In principle it is given by $G_M/C_C \sim$ THz, where $C_C \sim$ aF is the capacitance of the MOSFET constriction. For the measurement set up used in these experiments, the bandwidth was limited by the 400 kHz Femto current amplifier used to measure G_M.