Suppression of low-frequency noise in two-dimensional electron gas at degenerately doped Si:P δ layers

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We report low-frequency $1/f$-noise measurements of degenerately doped Si:P δ layers at 4.2 K. The noise was found to be over six orders of magnitude lower than that of bulk Si:P systems in the metallic regime and is one of the lowest values reported for doped semiconductors. The noise was nearly independent of magnetic field at low fields, indicating negligible contribution from universal conductance fluctuations. Instead, the interaction of electrons with very few active structural two-level systems may explain the observed noise magnitude.

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As classical information processing technology approaches the sub-20-nm node, it is becoming increasingly important to control the exact number and position of dopants in electronic devices.[1,2] Recent progress in using scanning-tunneling microscopy (STM) as a lithographic tool allows positioning of dopants with atomic scale precision.[3] Combined with molecular beam epitaxy, this technology has been employed to realize heavily δ-doped planar nanostructures such as tunnel gaps,[4] nanowires,[5] and quantum dots.[6,7] The same approach can also be used to fabricate vertically stacked multiple electrically active layers.[8] The time-averaged transport properties of Si:P δ-doped layers have now been studied in detail,[5–7,9] but very little is known about its long term charge stability, which reflects in low-frequency flicker noise in the electrical transport. The importance of this issue is paramount to the overall development of devices with controlled dopant positioning at the nanoscale and in particular for single-dopant spin-based qubits.[10]

The noise properties of bulk doped Si have been studied in the metallic regime as well as near the metal-to-insulator transition (MIT). While universal conductance fluctuations (UCF) have been observed in the metallic samples,[11] signatures of glassy behavior has been seen near the MIT.[12] The situation is far more unclear when the dopants are confined within one or very few atomic layers. This acquires additional significance due to stronger interaction effects at lower dimensions, theoretical predictions of exotic magnetic states,[13,14] and other possibilities of Hubbard physics close to half filling that are naturally realized in these δ-doped Si systems.

In this Letter we present the study of low-frequency noise, or $1/f$ noise, in degenerately doped Si:P δ layers. We perform noise measurements as a function of number of carriers to establish that the measured conductivity fluctuations originate from the δ layer. We find that the noise is many orders of magnitude lower than bulk doped metallic silicon. Though the magnetoconductivity data indicate weak localization (WL), the magnetic-field dependence of noise speaks against any significant contribution from UCF. Instead, the interaction of electrons with a small concentration of tunneling two-level systems (TLS) may explain the extremely low noise in these heavily doped systems.

Two Hall bars (S1 and S2) from the same δ-doped Si:P layer have been studied in this work. The Si:P δ layer was fabricated in an ultrahigh vacuum variable-temperature STM system equipped with a phosphine (PH_3) dosing system and a Si sublimation source. The details of sample fabrication have been reported elsewhere.[9] The trench-isolated Hall bars, were fabricated by electron-beam lithography and reactive ion etching. Figure 1(a) shows a schematic of the final device structure, wherein a δ layer of P atoms is indicated by the red (gray) line. Both Hall bars have a width of 20 μm and multiple voltage probes for carrier-number-dependent noise measurements. Ohmic contacts to the Hall bars were made by depositing 60 nm of nickel (Ni) and 10 nm of titanium (Ti), followed by annealing in nitrogen atmosphere at 350 °C and depositing another layer of Ti/gold (Au) (10 and 60 nm, respectively). An optical image of the device S2, recorded after deposition of the ohmic contacts, is shown in Fig. 1(b).

From Hall measurements at temperature $T = 4.2$ K, the two-dimensional (2D) electron density of both samples was estimated to be $n = (1.22 \pm 0.01) \times 10^{14}$ cm^{-2}. Both devices indicate a finite residual resistivity $\rho_0 \sim 600\ \Omega$/square, with $k_F\ell \simeq 40$ (k_F and ℓ are Fermi wave-vector and mean-scattering lengths, respectively). The initial decrease in resistivity ρ with decreasing T (from $T = 70$ to 12 K) in both devices (data for S2 not shown) confirms metallic-like behavior [see Fig. 1(c)]. The upturn in ρ for $T \lesssim 12$ K is associated with the WL effect. To probe this further, and also extract the phase relaxation length, L_ϕ, we have performed a four-probe magneto-conductance measurement at 4.2 K. Figure 1(d) shows the magnetoconductivity plot of S1, measured in a perpendicular magnetic field ($B_\perp$) at 4.2 K. The dip at $B_\perp = 0$ is the hallmark of WL behavior. The magnetoconductivity data were fitted with the Hikami formulation[15] for disordered 2D systems, which gives a phase-breaking field (B_ϕ) of ~60 mT and $L_\phi \sim 50$ nm at 4.2 K. For both resistance and noise measurements, the voltage drop across the device, V, was kept $\ll (k_BT/e)L/L_\phi$ to minimize heating of electrons.

For noise measurements we used an ac four-probe wheatstone bridge technique.[11,16,17] The voltage drop across the sample was amplified by a low-noise voltage preamplifier (SR 560) and the output of the amplifier was balanced across a

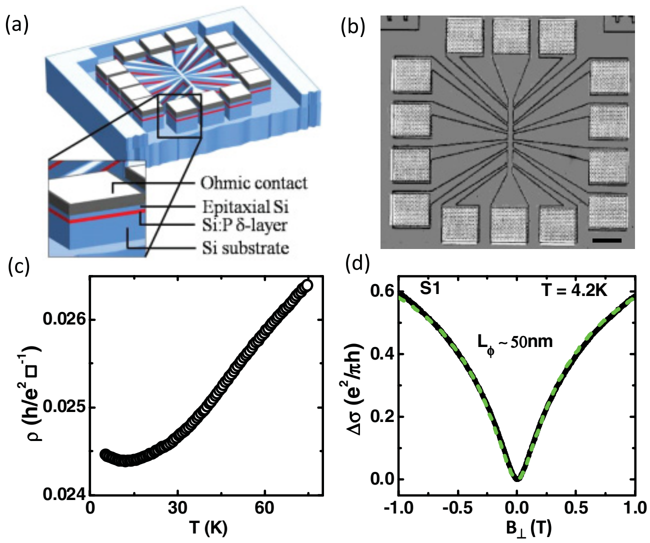

FIG. 1. (Color online) (a) Schematic of the device structure showing the δ layer (red/gray line) of P atoms inside Si. (b) Optical image (false color) of device S2 used in this experiment. The scale bar is 100 μm. (c) Resistivity vs temperature, T, for a device similar to the one studied in this work. (d) Magnetoconductivity plot for sample S1 at T = 4.2 K. The dashed line is the weak-localization fit to the data.

standard wire wound resistor. The voltage fluctuations were recorded as a function of time using a 16-bit digitizer. The raw data were then processed digitally using a three-stage decimation process, followed by the power-spectral-density (PSD) estimation. The details of the noise-measurement process can be found elsewhere.[16,17] The PSD, $S_V(f)$, of noise as a function of frequency, f, is shown in Fig. 2(a) for both samples. In both devices, we found $S_V \propto 1/f^{\alpha}$, where the frequency exponent $\alpha \approx 1$–1.2 over the entire experimental bandwidth. The bias dependence of S_V shown in Fig. 2(b) was recorded for different distances between the voltage probes for sample S1. The solid lines show linear fits to the data. S_V was found to be $\propto V^2$, for all cases, which ensures that we are in the ohmic regime, where the measured voltage fluctuations represent the fluctuations in ρ of the Si:P δ layer, i.e., $S_V/V^2 = S_\rho/\rho^2$. Moreover, the slope of the linear fits decreases as the separation between the voltage probe increases, which essentially means that S_ρ decreases as the total number of carriers increases.

The frequency and the bias dependence of noise can be combined to normalize the noise magnitude in terms of the phenomenological Hooge relation,

$$\frac{S_\rho(f)}{\rho^2} = \frac{\gamma_H}{nAf^{\alpha}}, \tag{1}$$

where γ_H, n, and A are the phenomenological Hooge parameter, the areal density of electrons, and the area of the Hall bar between the voltage probes, respectively. In the data shown in Fig. 2, the magnitude of γ_H was deduced to be around 10^{-6}, which is orders of magnitude lower than that of bulk doped Si:P systems degenerately doped to the metallic regime ($\gamma_H = 0.1$–2).[18,19] Given such a low value of γ_H, it is important to establish that we indeed are measuring the noise from the

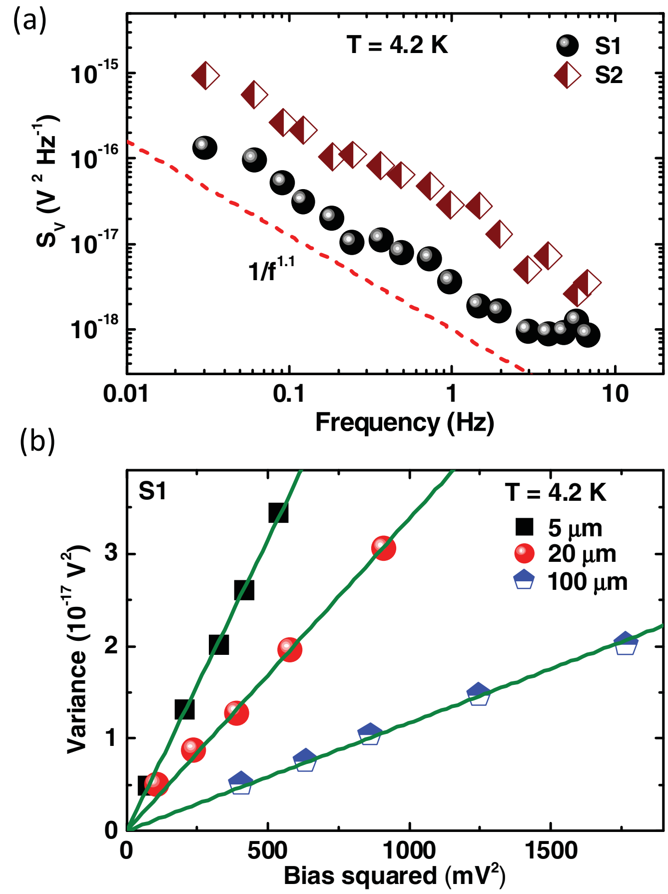

FIG. 2. (Color online) (a) The power spectral density (PSD), S_V, as a function of frequency for both devices at $T = 4.2$ K and zero magnetic field ($B_\perp = 0$). The dashed line indicates that the spectrum is $1/f$ in nature. The spectrum of S2 is offset by three times for visual clarity. (b) The PSD, S_V, as a function of V^2 for three different channel lengths of sample S1. The solid lines shows linear fits to the data.

δ layer. Noise measurements were performed for different distances between the voltage probes for both S1 and S2. The results are shown in Figs. 3(a) and 3(b), respectively, where $\langle\delta\rho^2\rangle/\rho^2$ is plotted against the area (A) of the δ layer between the voltage probes [here, $\delta\rho^2 = \int S_\rho(f)df$]. As expected from the Hooge relation, $\langle\delta\rho^2\rangle/\rho^2$ shows a $1/A$ dependence, confirming that the measured resistance fluctuations come from the Si:P δ layer where different fluctuators contribute independently to the observed noise magnitude.

In order to understand the microscopic origin of noise in Si:P δ layers, we have investigated the noise magnitude as a function of perpendicular magnetic field ($B_\perp$) for S1 at $T = 4.2$ K. We find that the γ_H remains essentially constant over the range corresponding to the phase-breaking field, B_ϕ, [see the inset of Fig. 3(a)], which is ~60 mT at $T = 4.2$ K. The near constancy of noise with $B_\perp$ shows that UCF as a major source of noise is quite unlikely as we do not see any factor of *two* reduction in γ_H[11,20] expected on removal of time-reversal symmetry. This is a surprising result since the magnetoresistance clearly displays WL [see Fig. 1(d)], and UCF and WL are expected to be manifestations of the same quantum-interference effect. It is, however, possible that the

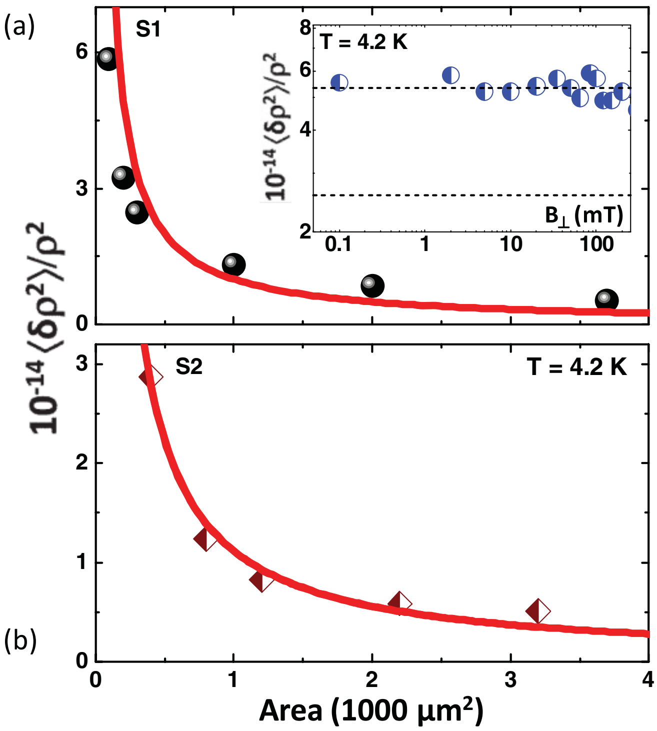

FIG. 3. (Color online) (a) The normalized variance $\langle\delta\rho^2\rangle/\rho^2$ as a function of area for S1 at $T = 4.2$ K and $B_\perp = 0$. (Inset) $\langle\delta\rho^2\rangle/\rho^2$ vs B at $T = 4.2$ K for S1. The dashed lines show average value for $\langle\delta\rho^2\rangle/\rho^2$ and $1/2 \times \langle\delta\rho^2\rangle/\rho^2$. (b) Variance $\langle\delta\rho^2\rangle/\rho^2$ as a function of area for S2 at $T = 4.2$ K and $B_\perp = 0$. The solid lines represent $1/A$ variation of noise magnitude.

low-temperature Hamiltonian of our δ-doped Si system has very different symmetry properties from conventional disordered conductors, although there is no clear understanding of why this should be so.

An alternative possibility is based on a local interference model suggested by Kogan and Nagaev[21] with anisotropic scattering of electrons by tunneling TLS. In our system, the TLS may be associated with the incorporation of P atoms in the silicon matrix, as indicated in the bulk-doped systems.[11] In this model, the resistivity fluctuations can be expressed as[21]

$$\frac{S_\rho(f)}{\rho^2} \approx \frac{n_{\rm TLS}(\ell\sigma_s)^2}{Af}, \qquad (2)$$

where $n_{\rm TLS}$ and σ_s are the areal density of the TLS and scattering cross section of the electrons, respectively. Note that γ_H in Eq. (2) is independent of B. Taking $\sigma_s \sim 1/\sqrt{n_P}$, we estimate $n_{\rm TLS}/n_P \simeq 2\pi\gamma_H[\rho_0/(h/e^2)]^2 \sim 3\times 10^{-7}$. This indicates that the magnitude of the observed noise can be explained if only three in ten million P atoms form active TLS within the experimental bandwidth. Note that charge fluctuations on even a small number of defects can have a $1/f$ spectrum as long as relaxation rates are widely distributed.[22]

It is well known that at extremely high dopant concentrations defects can occur creating deactivating centres either through the formation of donor vacancy clusters or donor pairs or donor-pair vacancy interstitials.[23–26] However, using a gaseous dopant source with self-limiting absorption of the gaseous dopant precursor, it is somewhat surprising

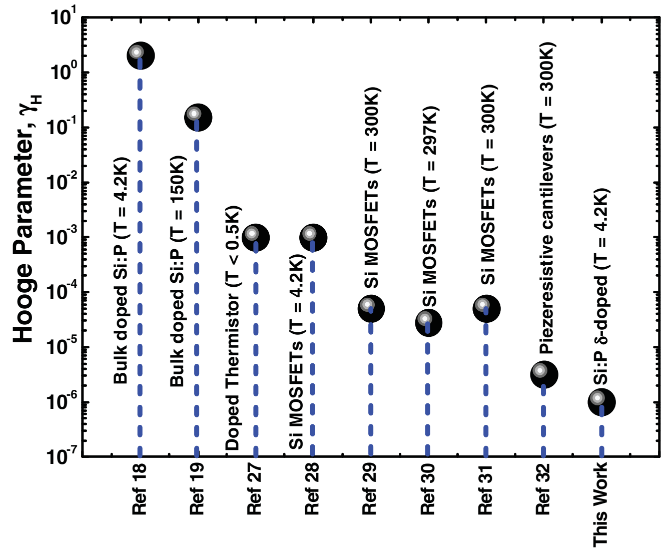

FIG. 4. (Color online) Comparison of various reported values of Hooge parameter, γ_H, for doped silicon. Since the noise magnitude can strongly depend on temperature (T), the values of T for each reference have been explicitly stated.

that such defect complexes would occur. Other possible explanations could be the incomplete incorporation of dopants into substitutional sites during the incorporation anneal or the potential presence of defects in the epitaxial silicon overgrowth. These results highlight that despite the extremely low noise observed, further work is needed to pinpoint exactly what gives rise to the noise floor in these heavily doped devices.

In Fig. 4, we compare the Hooge parameter of our system with the values reported previously for doped Si. Ghosh *et al.*[18] and Kar *et al.*[19] have previously measured highly doped bulk Si:P systems and found fairly large values of γ_H (0.1 to 2). In comparison to these bulk doped Si:P systems, we find that the noise in Si:P δ layers studied in this work is suppressed by five to six orders of magnitude. Other references included in Fig. 4 are for doped thermistors,[27] Si metal-oxide-semiconductor field-effect transistors (MOSFETs)[28–31] and piezoresistive cantilevers.[32] An explanation of the extremely low noise in our system may involve large elastic energy barriers around the P atom that immobilize them and reduce the number of active TLSs. Such barriers may arise during the doping process when the Si-Si bonds distort locally to incorporate the dopants. The remarkably low value of γ_H measured here favors the use of Si:P δ-doped devices as versatile nanoelectronic elements.

In conclusion, we demonstrated suppression of resistance noise in Si:P δ layers by several orders of magnitude, in comparison to degenerately doped bulk Si:P systems. The noise is nearly unaffected by low magnetic fields. We indicate the possible role of tunneling two-level systems within a local interference model to understand the microscopic origin of the noise.

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