Electrically Detected Magnetic Resonance of Neutral Donors Interacting with a Two-Dimensional Electron Gas

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We have measured the electrically detected magnetic resonance of donor-doped silicon field-effect transistors in resonant *X*- (9.7 GHz) and *W*-band (94 GHz) microwave cavities. The two-dimensional electron gas resonance signal increases by 2 orders of magnitude from *X* to *W* band, while the donor resonance signals are enhanced by over 1 order of magnitude. Bolometric effects and spin-dependent scattering are inconsistent with the observations. We propose that polarization transfer from the donor to the two-dimensional electron gas is the main mechanism giving rise to the spin resonance signals.

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Electrical spin-state detection for solid-state qubits requires a detection channel formed by conduction electrons in close proximity to the qubit. For electron spin qubits, the detection channels usually consist of quantum point contacts or single electron transistors, which are sensitive to the electrostatic environment nearby and able to detect the spin-dependent occupancies of electrons at the qubit site [1–4]. Alternatively, for nuclear spin qubits such as shallow donors in silicon [5], it was proposed that conduction electrons interacting *directly* with the donors can be used for nuclear spin-state readout [6,7], as the conduction and neutral donor electrons undergo spin-dependent scattering [8–12]. Donor-doped metal-oxide-semiconductor (MOS) devices provide an ideal platform for the detection of such an interaction, as the electronic wave function of neutral donors embedded in the device channel can overlap with the gate-induced two-dimensional electron gas (2DEG) nearby [Fig. 1(a)]. The donor-2DEG interaction can be probed by electrically detected magnetic resonance (EDMR), as was first demonstrated by Ghosh and Silsbee at ~0.35 T [8]. The results, however, were complicated by the overlap between the donor and 2DEG resonance signals due to the use of relatively highly doped substrates. In this Letter, we clarify the mechanisms behind the EDMR signals of such donor-doped MOS devices by performing EDMR with *n*-type accumulation-mode field-effect transistors (aFETs) at Zeeman fields of ~3.36 T and comparing it to low-field EDMR at ~0.35 T. We discuss our results in terms of (i) bolometric heating, (ii) spin-dependent scattering, and (iii) a polarization transfer from the donor to the 2DEG spin system.

Bolometric heating of the 2DEG [Fig. 1(c)] can occur when the 2DEG orbital electron temperature T_e rises as a result of an increase of the 2DEG spin temperature (i.e., a decrease in the 2DEG spin density polarization p_c) via spin-orbit interaction [13]. The energy transfer from the 2DEG spins to the lattice occurs through T_{1c} relaxation processes and from donor spins through T_x flip-flop processes via exchange scattering with the 2DEG. This effect is expected to be enhanced at higher magnetic fields as the absorbed Zeeman energy on resonance is increased.

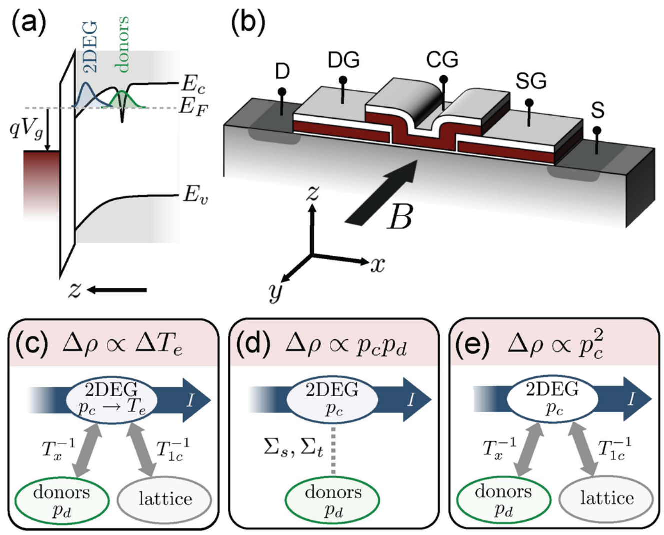

FIG. 1 (color online). (a) Energy-band diagram of the MOS system showing the overlap of the 2DEG and donor electron wave functions. (b) Schematic of the aFET used, where the drain (D) and source (S) are separated by three gates (DG, CG, and SG). ^{31}P donors are present under all three gates while ^{75}As donors reside under the CG region only. (c–e) Three possible EDMR mechanisms affecting the 2DEG current *I* (dark blue arrow), and the expected change in resistivity $\Delta\rho$ associated with each mechanism: (c) bolometric heating, (d) spin-dependent scattering, and (e) polarization transfer. The light grey arrows represent energy transfer between the systems, while the dashed line in (d) represents elastic scattering. See text for the definition of symbols.

Spin-dependent scattering arises from a difference in the scattering cross sections Σ_s and Σ_t when the 2DEG and donor electrons form singlet (s) and triplet (t) pairs, respectively, [Fig. 1(d)]. The number of singlet pairs is increased when either the donor or 2DEG spins are resonantly excited. This leads to a change in sample resistivity of $\Delta\rho/\rho_0 \propto p_c p_d$ under full power saturation, where ρ_0 is the resistivity in thermal equilibrium, and p_d the spin density polarization of the donor electrons [8]. For an ideal 2DEG, $p_c \propto g\mu_B B$, where g is the Landé g factor, μ_B the Bohr magneton, and B the magnetic field. For donors, $p_d = \tanh(g\mu_B B/k_B T)$, with k_B the Boltzmann constant and T the temperature. This implies that the 2DEG and donor resonance signals should have the same magnetic field dependence as only the product of the polarizations $p_c p_d$ is measured under this mechanism.

The third mechanism we consider results from the polarization dependence of the 2DEG resistivity [14–16], as was found to be the case for EDMR of high mobility silicon 2DEGs [17,18]. Donor electrons can contribute to a resonant change in 2DEG resistivity as the donor polarization is transferred to the 2DEG spin system via exchange scattering [Fig. 1(e)]. The observation of this effect is only possible if spin-orbit coupling is weak and T_e is not perturbed excessively, as the bolometric response will dominate otherwise. These three mechanisms form the basis for the detailed discussion of our results below.

A schematic of the aFET used is shown in Fig. 1(b). The device was fabricated on 1 μm thick 99.95% isotopically purified 28-silicon (^{28}Si), grown epitaxially on a high resistivity natural silicon substrate. The aFET has a triple-gate geometry with two 60 μm long side gates and one 40 μm long center gate, with a channel width of 40 μm and 20 nm gate oxide thickness throughout. For this study all three gates are biased together and the whole device is considered as a simple three-terminal FET. The ^{28}Si layer is background doped with 3×10^{16} cm^{-3} phosphorus (^{31}P) donors, while the center region received an additional implantation of arsenic (^{75}As) donors at 50 keV and a dose of 4×10^{11} cm^{-2}. Secondary ion mass spectroscopy shows that ^{31}P and ^{75}As have peak concentrations of 1×10^{17} cm^{-3} and 5.5×10^{16} cm^{-3}, respectively, close to the gate oxide interface. From the geometry of the device, 6×10^5 arsenic and 4×10^6 phosphorus donors reside within 10 nm of the oxide interface where they can interact with the 2DEG directly. A silicon dioxide–aluminum microwave shunt is deposited over the sample to minimize microwave-induced rectification noise [19].

We carried out EDMR measurements in Bruker ElexSys E680 X- (9.7 GHz) and W-band (94 GHz) microwave resonators with corresponding Zeeman fields of ~0.35 T and ~3.36 T, respectively [20]. A lock-in technique at 5.02 kHz and 0.2 mT field modulation was used to improve the signal-to-noise ratio. All measurements were carried out at 5 K where the device has a threshold voltage of 0.25 V and an effective mobility of 12 000 cm^2/V s. The Zeeman field is aligned in the plane of the 2DEG, perpendicular to the direction of current flow. No change in the device current-voltage characteristics was observed for the two Zeeman fields.

The EDMR spectra obtained are the first derivative of the change in device resistivity $\partial(\Delta\rho/\rho_0)/\partial B$, and typical results are shown in Fig. 2. We have checked the sign of the signals carefully by both tracing through phase shifts in the measurement setup and by measuring the dc change in sample resistivity directly on and off resonance in W band. Both measurements confirm that the resonance peaks have a negative sign upon resonance, i.e., $\Delta\rho/\rho_0 < 0$.

Three groups of lines can be identified in the X-band spectrum [Fig. 2(a)]: The intense center line has a g factor of 1.9999 and is assigned to the 2DEG [21,22]. The two adjacent peaks, split by 4.2 mT and with a center-of-gravity g factor of 1.9987, correspond to ^{31}P donors with a nuclear spin of 1/2 [23]. Four smaller satellite peaks farther out on both sides are split by 7.1 mT and arise from ^{75}As donors with a nuclear spin of 3/2 [23]. The same three groups of lines are seen in the W-band spectrum [Fig. 2(b)], centered at 3.358 T. The 2DEG coincides with the low-field ^{31}P line due to the different g factors. We define the signal intensity of a resonance line as the amplitude of the integrated spectrum, i.e., $\Delta\rho/\rho_0$. With the spin transitions being saturated, the signal intensities increase from X to W band by a factor of ~100 and ~20 for the 2DEG and donors, respectively. The relative ratio between the ^{31}P and ^{75}As signal intensities is consistent with the total number of dopants under the channel and the number of hyperfine-split resonance lines.

In order to assess the possible contribution of bolometric heating of the 2DEG to the EDMR signal, we measured the

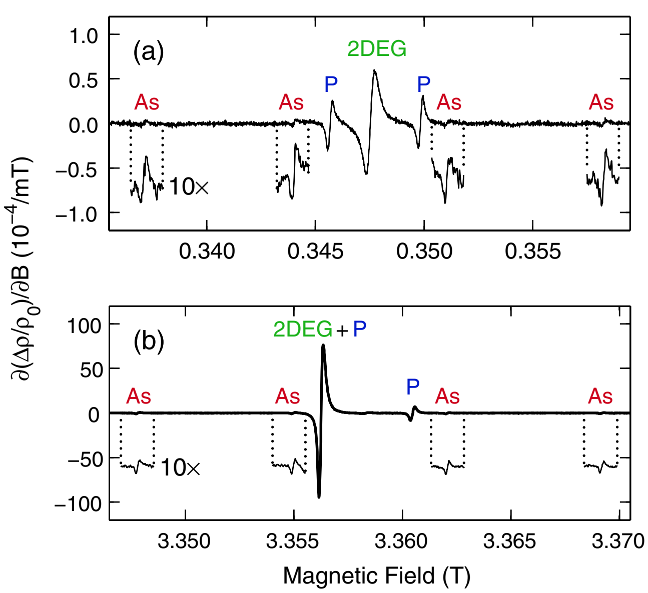

FIG. 2 (color online). (a) EDMR spectra obtained in X and (b) W band. The 2DEG, phosphorus (P) and arsenic (As) resonances are indicated along the traces. Sections of the EDMR spectra are magnified by 10× and offset for clarity. The gate bias was 0.3 V and the drain bias was 40 mV in both measurements.

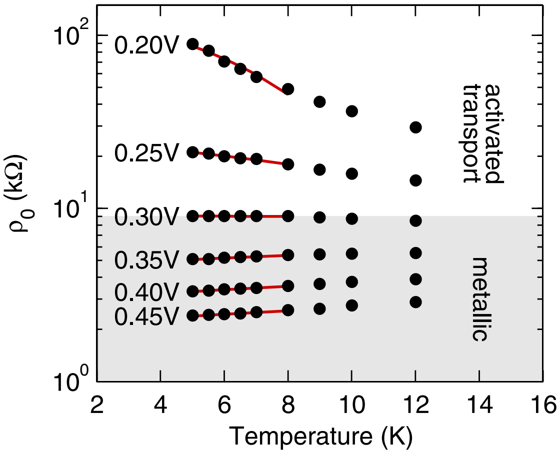

FIG. 3 (color online). Temperature dependence of device resistivity for gate voltages $V_g = 0.20$–0.45 V. Solid lines correspond to linear fits to the data for $T \leq 8$ K.

device resistivity over the temperature range $T = 5$–12 K as shown in Fig. 3. At these temperatures, acoustic phonon scattering does not contribute to the overall carrier mobility significantly [24,25]. Hence, any temperature dependence of the resistivity is a result of changes in T_e only and independent of the lattice temperature T_l. We observe that carrier transport can be separated into two regimes: (i) $\partial\rho_0/\partial T < 0$ for $V_g < 0.3$ V, the activated transport regime, and (ii) $\partial\rho_0/\partial T > 0$ for $V_g > 0.3$ V, the metallic regime. For bolometric heating one would expect the sign of $\Delta\rho/\rho_0$ to follow the sign of $\partial\rho_0/\partial T$. Hence, the sign of the EDMR signal should change at around $V_g = 0.3$ V. Our EDMR experiments do not reveal any change in sign, and disagree with the temperature gradient for $V_g > 0.3$ V. We thus conclude that bolometric heating does not contribute to the EDMR signal significantly.

Previous EDMR measurements of similar donor-doped FETs at X band have been attributed to spin-dependent neutral donor scattering [8,9]. de Sousa, Lo, and Boker [12] recently calculated the scattering cross sections for such systems and concluded that $\Sigma_s > \Sigma_t$ (i.e., $\Delta\rho/\rho_0 > 0$), which contradicts the results of Ghosh and Silsbee as well as ours. We note, however, that a refined calculation taking the full anisotropy of the silicon band structure into account might lead to cases where $\Sigma_s < \Sigma_t$ [26]. The neutral donor scattering model also predicts the 2DEG signal intensity to be equal to the sum of the hyperfine-split donor signal intensities, while our results show that the 2DEG signal intensity is much greater than the sum in both X and W band. This can only be the case if spin-dependent scattering with other paramagnetic centers, such as P_b centers [27], also contributes to the 2DEG signal. Such resonance signals were, however, not observed in our experiments. Finally, from the increase in thermal equilibrium polarizations we expect the spin-dependent scattering signal to be enhanced by a factor of 80 at $T = 5$ K from X to W band. Over the gate bias range examined, with corresponding 2DEG densities of 5.0×10^{10}–$1.5 \times 10^{11}/\text{cm}^2$, we have found that the 2DEG enhancement is stronger than expected, while the donor enhancement is substantially smaller. Because of these inconsistencies it is difficult to explain our results by this mechanism alone.

We thus propose a third EDMR mechanism, which originates from the polarization-dependent resistivity of the 2DEG [17,18,28,29]. We assume the 2DEG resistivity to be approximated by $\rho = \rho_1 + \rho_2 p_c^2$, where ρ_1 and ρ_2 are the polarization-independent and polarization-dependent components, respectively. Assuming a complete saturation of the 2DEG spin transition, we have $\Delta\rho/\rho_0 \approx -p_c^2/(\rho_1/\rho_2)$ for the 2DEG as $\rho_1 \gg \rho_2$. From the positive in-plane magnetoresistance ($\partial\rho/\partial B > 0$), i.e., positive correlation between 2DEG resistivity and p_c [14–16], we expect $\rho_2 > 0$. Thus, this model agrees with the negative sign of the EDMR signal observed in our experiments. At X band, we estimate that $p_c \approx 1\%$ with the 2DEG densities used, and since $\Delta\rho/\rho_0 \approx -10^{-5}$, we have $\rho_1/\rho_2 \approx 10$. Since $p_c \propto B$, the 2DEG signal should increase by 100 times from X to W band, which is consistent with our observations. The signal intensities of the donors depend on the effectiveness of the donor-to-2DEG polarization transfer, which is determined by (i) the spin relaxation rate of the 2DEG T_{1c}^{-1}, and (ii) the spin exchange scattering rate T_x^{-1} [30], which varies from donor to donor depending on their distance to the oxide interface [12] (we assume the spin relaxation rate of donors to be much smaller than that of the 2DEG [21,22,31,32]). If $T_x^{-1} \ll T_{1c}^{-1}$, p_c returns to its thermal equilibrium rapidly, and the change in p_d has little effect on p_c. Therefore, no donor resonance signal should be observed. In the opposite limit where $T_x^{-1} \gg T_{1c}^{-1}$, p_c and p_d are strongly coupled and indistinguishable. In this case one would expect the 2DEG and donor signal intensities to be equal, which was not observed. Since T_x^{-1} does not change much with the magnetic field in the temperature range of our experiments [33], the different 2DEG and donor signal intensity ratios between W and X band can be explained if T_{1c}^{-1} becomes larger at higher magnetic fields: Donors with $T_x^{-1} \gtrsim T_{1c}^{-1}$ at X band will be less effective in influencing p_c in W band as $T_x^{-1} < T_{1c}^{-1}$ now. This implies that a reduced number of donors can contribute to the donor resonance signal in the high-field measurements, which is consistent with the observed increase in the 2DEG-to-donor signal intensity ratio in W vs X band. We are unaware of any experimental measurements of the magnetic field dependence of T_{1c}^{-1} in the metallic limit of a disordered 2DEG. However, due to increased polarization in the W band, the total T_{1c}^{-1} relaxation rate should also increase proportionally, in agreement with our observations.

In the case where the spin transitions are not fully saturated, from the standard Bloch equations we expect the polarization on resonance to be $p = p_0/(1 + \gamma^2 B_1^2 T_1 T_2)$, where p_0 is the polarization in thermal equilibrium, γ the gyromagnetic ratio, B_1 the amplitude of the microwave

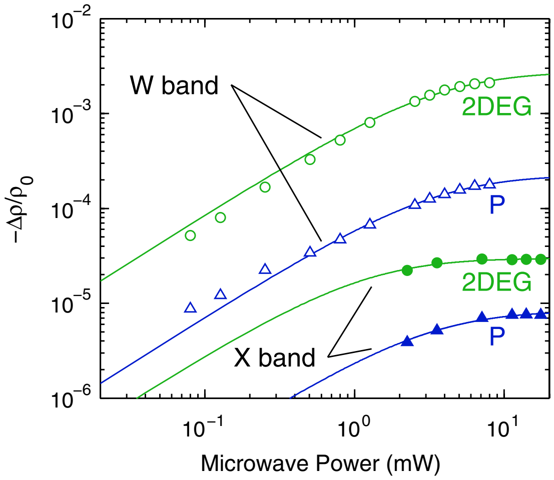

FIG. 4 (color online). Microwave power dependence of the 2DEG (green circles) and ^{31}P (blue triangles) EDMR signal intensities measured in X (closed symbols) and W band (open symbols). The lines represent best fits to $\Delta\rho/\rho_0$ as described in the main text. ^{75}As signals have similar power dependences and are not shown. The gate bias was 0.3 V in all measurements.

magnetic field, and T_2 the spin coherence time. Figure 4 shows the microwave power dependence of the 2DEG and phosphorus EDMR signal intensities measured in both the X and the W band. Since the magnitude of B_1 is unknown, we fit the observed power dependence to $\Delta\rho/\rho_0 \propto (p_c^2 - p_{c0}^2) \propto [1/(1+\beta P_{\mu w})^2 - 1]$, where $\beta P_{\mu w} = \gamma^2 B_1^2 T_1 T_2$ is the fitting parameter. The good agreement between the measured power dependencies of the EDMR signals and the fits to p_c^2 dependencies further support our polarization transfer model.

In conclusion, we have performed systematic EDMR studies of silicon field-effect transistors in resonant X- and W-band microwave cavities. Our findings of decreasing device resistance on resonance and a much stronger magnetic field dependence of the EDMR signal intensities of the 2DEG over donors are in conflict with both bolometric effects and spin-dependent neutral donor scattering as dominant underlying mechanisms. We have shown that these observations are consistent with a polarization-dependent 2DEG mobility model, where donors contribute to EDMR by polarization transfer to the 2DEG spin system.

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