Suppression of microwave rectification effects in electrically detected magnetic resonance measurements

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Spin-dependent transport properties of micro- and nano-scale electronic devices are commonly studied by electrically detected magnetic resonance (EDMR). However, the applied microwave fields in EDMR experiments can induce large rectification effects and result in perturbations of the device bias conditions and excessive noise in the EDMR spectra. Here we examine rectification effects of silicon metal-oxide-semiconductor field-effect transistors exposed to X-band microwave irradiation and show that the rectification effects can be effectively suppressed by incorporating a global capacitive shunt covering the device. We demonstrate that the signal-to-noise ratio in the EDMR spectra improves by over a factor of ten in the shunted devices. [doi:10.1063/1.3684247]

Electrically detected magnetic resonance (EDMR) is a versatile technique for studying spin-dependent transport phenomena in electronic devices. Instead of monitoring the microwave absorbed by the sample upon spin resonance as in conventional electron paramagnetic resonance (EPR), the change in electrical transport characteristics of the device is measured in EDMR, and it has been shown that EDMR offers orders of magnitude higher spin number sensitivity compared to EPR.[1,2] EDMR provides spectroscopic information like the g-factor and hyperfine interactions of charged carriers in the host material, thus elucidating the microscopic environment seen by the carriers.[3–6] In addition, understanding the spin-dependent transport mechanisms, such as spin-dependent recombination,[1,7,8] trapping,[9–11] tunneling,[12] and scattering[13–17] allows access to the spin dynamics useful for spin-based quantum information processing.[18]

A common approach to EDMR involves placing the device of interest into an EPR microwave resonator, with the most popular being X-band (9–10 GHz) measurements. However, a typical problem associated with such EDMR setup is microwave-induced rectification in the device, which can both adversely affect the bias conditions of the device and generate excessive noise in the EDMR measurements. In this paper, we examine microwave rectification in silicon metal-oxide-semiconductor field-effect transistors (MOSFETs) measured in a X-band rectangular TE_{102} resonator. We demonstrate a simple solution to the rectification problem by incorporating a global capacitive shunt covering the device.

In a typical EDMR setup, the active region of the device is placed in the resonant microwave cavity where the microwave magnetic field (B_1) is at its maximum and the microwave electric field (E_1) at a minimum (Fig. 1(a)). Metallic wires are then used to connect the device to the bias and detection circuitries located outside of the cavity. However, microwave-induced voltage fluctuations can be inadvertently picked up by the sample and the metallic wires. In case of a MOSFET, these voltage fluctuations $v_{i,\mu w}$ ($i = \{s(\text{source}), d(\text{drain}), g(\text{gate})\}$) will be superimposed to the external bias V_i of the device (Fig. 1(b)). $v_{i,\mu w}$ can arise from (i) magnetic induction of the oscillating B_1 field in the current loop consisting of the device and the biasing circuitry[19–21] and/or from (ii) coupling of the E_1 field with metallic wires of the

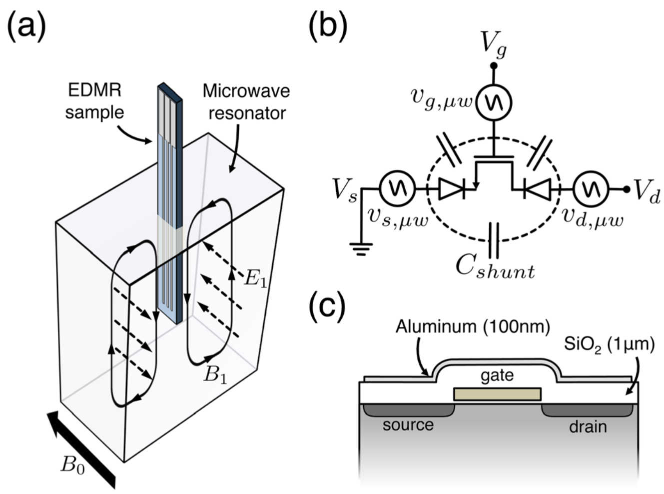

FIG. 1. (Color online) (a) Schematic of the EDMR setup with an X-band TE_{102} microwave cavity. The Zeeman (B_0), microwave magnetic (B_1), and electric (E_1) fields are also shown. (b) Circuit diagram representation of the high frequency voltage fluctuations induced on the MOSFET in the EDMR setup, with non-ideal metal-silicon contacts represented by diodes. The shunt capacitor (C_{shunt}, dashed lines) can suppress the high frequency voltage fluctuations and resulting rectification effects. (c) Schematic of the implementation of shunt capacitors with our MOSFETs.

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device. Even though the device is usually placed in a node of the E_1 field in the cavity, the tangential E_1 fields on the surface of the device can be quite substantial because the microwave fields are strongly distorted with a dielectric sample placed in the cavity.[22] In addition, the long metallic lines can act as a microstrip-like resonator further enhancing the local field strengths at the device.[23]

For samples with perfectly ohmic current-voltage (*I*-*V*) characteristics, the high frequency voltage fluctuations $v_{i,\mu w}$ would cancel out in time-averaged measurements. However, MOSFETs are inherently non-linear devices,[19,20] and the metal-semiconductor contacts are often non-ohmic, especially at low temperatures. Therefore, $v_{i,\mu w}$ do not cancel out but instead are rectified in MOSFETs, leading to dc bias offsets in time-averaged measurements. Furthermore, mechanical vibrations and varying microwave fields seen by the device can lead to fluctuating bias offsets which shows up as excessive noise in subsequent EDMR measurements. The fluctuating voltages can also induce trapping and detrapping events of charged carriers in the MOSFET channel, producing additional noise with a broad power spectrum.[24] Here we demonstrate one possible way of suppressing the rectifying voltages and the excessive noise in EDMR experiments through incorporating a large capacitive shunt across the active region of the device, as shown in Fig. 1(c). We show that the capacitive shunt shortens out the high frequency voltage fluctuations and effectively suppresses the rectification effects.

The n-type MOSFETs were fabricated on high resistivity ⟨100⟩ silicon substrates, with 20 nm thick gate oxides. The device channel length was 80 μm and the width 5 μm. 300 nm thick aluminum was used to contact the $n+$ doped source-drain regions of the MOSFETs and form large bonding pads located approximately 20 mm away from the active region of the devices. The samples were then diced into elongated chips 25 mm in length and 2 mm in width, with one MOSFET per chip located 1 mm away from one edge of the chip. Thus, the large bond pads are located well outside of the approximately 30 mm long X-band microwave cavity when the active region of the sample is positioned at the center of the cavity (Fig. 1(a)). For devices with shunt capacitors, 1 μm thick silicon dioxide and 100 nm thick aluminum were deposited over all metal lines and covering the MOSFETs themselves, as shown in Fig. 1(c). An X-band EPR spectrometer (Bruker ESP300E) operating at 9.44 GHz with a rectangular TE_{102} microwave cavity was used. All measurements were carried out at a temperature of $T = 4.8$ K and with $\theta = 90°$, where θ is the angle between the normal of the silicon chip and the applied Zeeman field (B_0).

Fig. 2(a) shows the *I*-*V* characteristics of a MOSFET *without* a capacitive shunt. The *I*-*V* traces were first recorded with the microwave turned off and then with the microwave power set to the maximum of 200 mW. Under the latter condition, significant microwave-induced rectification is observed as evident by the large offset currents. The *I*-*V* measurements were performed on an identical device but *with* a capacitive shunt, and the results are shown in Fig. 2(b). The *I*-*V* characteristics of the shunted device look essentially identical regardless of the microwave power applied, proving the effectiveness of the shunt capacitor in

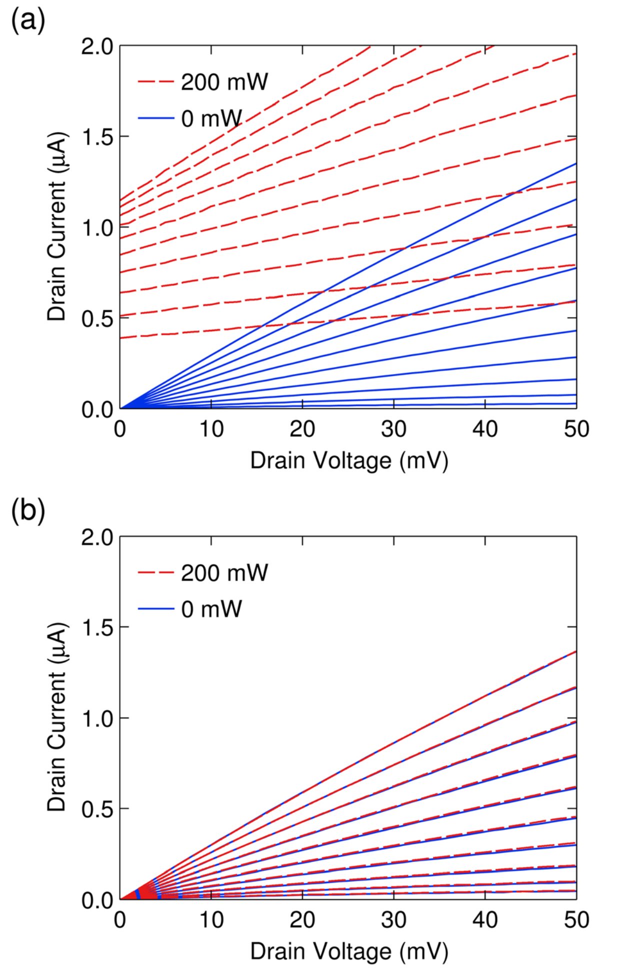

FIG. 2. (Color online) *I*-*V* characteristics of MOSFETs measured at $T = 4.8$ K with microwave power turned off (0 mW, blue solid traces) and set to the maximum (200 mW, red dashed traces): (a) device without a microwave shunt and (b) device with the overlaying microwave shunt. The gate voltages were adjusted from 300 mV to 750 mV in 50 mV increments from bottom to top in both plots. All measurements were performed with $\theta = 90°$

reducing the rectification effects. We have checked that the inclusion of the thin shunt layer had no effect on the cavity Q- factor (≈1300), ensuring that the same microwave power was delivered to both devices.

The use of the shunt capacitor is only beneficial for EDMR experiments if the additional metallic layer does not block the microwave magnetic field from coupling to the active region of the device. In Fig. 3 we show the EDMR signals from the shunted and unshunted devices measured under identical conditions. The resonance signals observed originate from conduction electrons in the channels of the MOSFETs, and details of the EDMR mechanisms in MOSFETs have been discussed elsewhere.[17] The shunted device shows approximately the same signal intensity as the unshunted device, proving that the microwave B_1 field is still effectively coupled to the shunted device. On the other hand, the shunted device exhibits a 15 times enhancement in signal-to-noise ratio over the unshunted one, demonstrating the effectiveness of the capacitive shunt in filtering out noise induced by microwave rectification effects.

We have also measured the rectification effects with other device orientations in the cavity. For $\theta = 0°$, where the

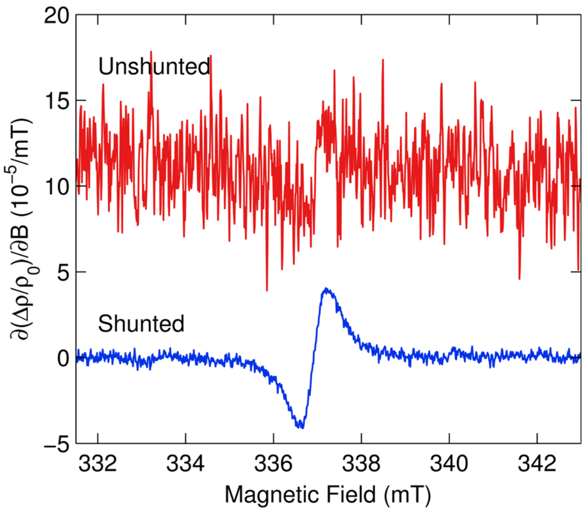

FIG. 3. (Color online) EDMR spectra of MOSFETs without (upper red trace) and with (lower blue trace) a capacitive shunt, offset for clarity. Both spectra were recorded with 200 mW microwave power. Magnetic field modulation at 1.56 kHz and modulation amplitude of 0.4 mT were used.

B_0 field and the microwave electric field E_1 are both normal to the silicon chip, the unshunted device showed approximately 10% higher rectification-induced offset currents compared to that shown in Fig. 2(a) with $\theta = 90°$. Nevertheless, the shunted device again completely suppressed the offset currents as well as the background noise in EDMR. In addition, we have made similar measurements in cylindrical resonant microwave cavities (Bruker MD4 dielectric resonators) and found comparable reductions in rectification effects and background EDMR noise. We have further measured similar devices in a W-band ($\approx$100 GHz) cylindrical microwave cavity and have found that the same capacitative shunt design works equally well at the higher microwave frequency.[2]

While we demonstrated the suppression of microwave rectification effects with MOSFETs, the use of the shunt capacitor is generally applicable to other transport experiments where microwave irradiation is required. One example is spin-dependent recombination experiments,[1,6–8,25–28] where having a metallic shunt layer covering the device would obstruct the above-band-gap illumination needed for photocarrier generation in this experiment. We have tested MOSFET EDMR samples with the metallic shunt layer covering the metal lines only and terminating 10 μm away from the active region of the MOSFET and found this design to be equally effective in suppressing microwave-induced rectification in X-band systems.

In conclusion, we have shown that microwave-induced rectification is of significant concern for resonant microwave cavity-based EDMR measurements. This rectification behavior with MOSFETs is experimentally verified utilizing an X-band microwave cavity. We have developed a shunt capacitor to suppress such rectification effects, and have found more than 10 times enhancement in the signal-to-noise ratio in EDMR measurements.

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