Microwave Irradiation Effects on Random Telegraph Signal in a MOSFET

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We report on the change of the characteristic times of the random telegraph signal (RTS) in a MOSFET operated under microwave irradiation up to 40 GHz as the microwave field power is raised. The effect is explained by considering the time dependency of the transition probabilities due to a harmonic voltage generated by the microwave field that couples with the wires connecting the MOSFET. From the dc current excited into the MOSFET by the microwave field we determine the corresponding equivalent drain voltage. The RTS experimental data are in agreement with the prediction obtained with the model, making use of the voltage data measured with the independent dc microwave induced current. We conclude that when operating a MOSFET under microwave irradiation, as in single spin resonance detection, one has to pay attention into the effects related to microwave irradiation dependent RTS changes.

The Random Telegraph Signal (RTS), observed as a random switching between two states of the channel current in a metal-oxide-semiconductor field effect transistor (MOSFET) [1, 2, 3, 4], has been considered as a possible quantum readout mechanism by Vrijen et al. [5] and has been used for detecting single electron spin resonance [6]. The spin resonance detection requires the irradiation by a microwave field of a defect at the Si/SiO$_2$ interface of a MOSFET in presence of a static magnetic field [7, 8]. The capture $\lambda_c$ and emission $\lambda_e$ rates due to the tunneling of electrons assisted by multiphonon non radiative processes depend on the energy levels of the trap with respect to the Fermi energy of the electron channel [9]. The change in the rates, at the resonance frequency, is due to the microwave-induced transition between the Zeeman energy levels of the trap. The RTS change at the spin resonance is detected by monitoring either the average drain-source current or the emission and capture times as a function of the static magnetic field while irradiating the device with a fixed microwave field [10].

The RTS change in spin resonance condition is detected by monitoring either the average drain-source current, or the emission and capture times as a function of the static magnetic field while irradiating the device with a microwave field. In both cases one should carefully identify proper experimental conditions in order to avoid spurious resonances induced by other traps in the MOSFET. We have already shown that the average current method is affected by a microwave induced stationary drain-source current [11].

In this letter we demonstrate that also the emission and capture times of the trap may change as a function of the intensity of the microwave field. To this aim, we have systematically characterized a change of the mean emission time $\tau_e$ and capture time $\tau_c$ of a trap at the interface between silicon and oxide in n-MOSFETs interacting with a microwave field. The devices are made on a p-well, with channel length of 0.35 $\mu$m, width of 0.45 $\mu$m, an oxide thickness of 7.6 nm, a threshold voltage of about 460 mV, and a transition frequency of several tens of GHz. All the contacts of source, drain, gate, and well were directly accessible through the bonding pads and connected to wires. The current $I_D$ flowing through drain and source is measured by a transimpedance amplifier whose output is sampled and digitized for off-line processing. The bandwidth of the amplifier extends to about 240 kHz allowing to characterize traps down to few microsecond characteristic times. The microwave source is a dipole antenna placed in front of the device, operating in a broad frequency range from 1 GHz to 40 GHz. The reported power refers to the power of the microwave generator at the source.

Figure 1 shows the variation of emission (down triangles, low current state) and capture (up triangles, high current state) characteristic times of our sample, in a given condition of MOSFET biasing, as a function of the microwave power, the frequency remaining fixed at $\nu =$ 15.26 GHz. The figure shows that in the trap under investigation the characteristic time $\tau_e$ is a function of the microwave power, while $\tau_c$ is constant.

The effect shown in Figure 1 can be fully ascribed to the inevitably present coupling between the microwave field and the conductive loop formed by the MOSFET and the connections toward the sensing amplifier: the microwave field induces a harmonic current on the loop, modulating the source and drain voltages of the MOSFET. In circuital representation, this corresponds to adding two AC voltage generators at the drain and at the source of the MOSFET (see Figure 2) with the same frequency of the microwave field. As shown in Figure 3, in

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static condition the characteristic times $\tau_c$ and $\tau_e$ change as a function of $V_D$. Exploiting the change of the field distribution in the proximity of the dipole antenna as a function of the frequency of the microwave, we are able to set a frequency where the coupling of the MOSFET with the microwave field occurs only at the drain. To set such condition we used a microwave frequency of 15.26 GHz. At room temperature, without microwave field applied and at $V_D = 800$ mV, the RTS has a mean capture time $\tau_c$ ranging monotonically from 3 ms to 20 ms for a drain voltage variation from 200 to 800 mV, while the mean emission time $\tau_e$ remains almost constant at about 0.7 ms.

In order to correlate the results of Figure 3 with those of Figure 1 obtained with the drain-source voltage oscillating at the microwave frequency, we calculated from Figure 3 the instantaneous capture and emission probabilities (per unit time), $\lambda_c$ and $\lambda_e$, as the inverse of the mean times for any drain voltage: $\lambda_c(V_D) = 1/\tau_c(V_D)$ and $\lambda_e(V_D) = 1/\tau_e(V_D)$. The modulation of $V_D(t)$ induced by the microwave field implies a modulation of the capture and emission probabilities $\lambda_{c,e}(V_D(t))$. Since the microwave frequency $\nu$ has a period $T = 1/\nu$ much shorter than the RTS characteristic times, we assume that the capture and emission processes are controlled by the average probabilities: $\lambda_{c,e} = 1/T \int_0^T \lambda_{c,e}(V_D(t))dt$, where the integration is performed over the period $T$ of the microwave field. Since generally $\lambda_{c,e}$ are not linear functions of $V_{DS}$, the average value calculated by integrating over a period differs from the value that the probability assumes when the amplitude of the harmonic voltage is zero.

In this framework, the characteristic times with a microwave field applied can be obtained as $\tau_{c,e} = 1/\lambda_{c,e}$. To quantitatively determine the value of $\tau_{c,e}$ as a function of the microwave power, it is necessary to determine the amplitude $\nu_{ac}$ of the modulating voltage at the drain induced by the microwave field.

To calculate such amplitude at each microwave power applied, we profit from the fact that a dc stationary current is also generated as the microwave field is raised due to the rectification produced by the non-linear I-V characteristic of the MOSFET. The current can be fitted by calculating the average of the current values as a function of the drain voltage around the bias value of $V_D$, weighted properly on a period, and setting the voltage amplitude as the only free parameter to be determined. The voltage amplitude can now be converted into the nominal microwave power $P_{\mu W}$. The experimental data of the dc current as a function of the microwave power are reported in Figure 4. From these data we obtain: $\nu_{ac} = 1.15[V/W^{1/2}] \cdot \sqrt{P_{\mu W}}$. Such relationship is used to predict the change of $\tau_c$ as a function of the microwave field power (Figure 1), in excellent agreement with the experiment. The constancy of $\tau_e$ (Figure 1) with respect to the microwave power agrees with the independence of $\tau_e$ of $V_D$. Different traps may have an opposite behaviour if $\tau_c$ is independent of $V_D$ or a mixed one if both $\tau_c$ and $\tau_e$ depend on $V_D$.

Such an agreement between the RTS variations and the microwave power has been confirmed on a variety of experiments carried out on various samples held in significantly different experimental conditions: samples inserted in resonant cavities operating at frequencies in X-band (9.5 GHz) and Q-band (34 GHz), different temperatures from 1 K to 300 K and also hybrid conditions when both the source and the drain are coupled to the microwave field.

To summarize, the inevitably present electric loop due to the on-chip and off-chip connections of a MOSFET to the external measuring system is responsible for the detected RTS variation upon microwave irradiation through the modulation of the MOSFET biasing conditions. Such an effect has important consequences on single-spin resonance experiments. A spurious microwave absorption in the environment may vary the effective power of the microwave field coupled with the MOSFET and produce a change of the RTS characteristics not related to the trap - responsible for the RTS - driven in spin resonance conditions. Any measured $\tau_c$, $\tau_e$ and dc current change in agreement with the proposed model prediction at a given power absorption has to be regarded as a spurious effect and cannot be ascribed to a single spin resonance phenomenon.

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I. FIGURE CAPTIONS

Fig.1  Experimental mean capture (up triangles) and emission (down triangles) times versus microwave field power compared to the theoretical predictions (continuous lines). Experimental conditions: $V_G = 800$ mV, $V_D = 500$ mV, $\tau_{c0} = 14$ ms, $\tau_{e0} = 0.7$ ms, $\nu = 15.26$ GHz.

Fig.2  Electrical circuit of the loop formed by the MOSFET and the sensing amplifier (not irradiated by the microwave field) coupled to the microwave field. The voltage induced by the field is represented by the two voltage generators $v_{d\mu w}$ and $v_{s\mu w}$.

Fig.3  Experimental capture (up triangle) and emission (down triangle) time constants as a function of the drain voltage for $V_G = 800$ mV and $V_S = 0$ V.

Fig.4  Measurement (circles) and simulation (continuous line) result of the dc drain current as a function of the microwave field power. Experimental conditions: $V_G = 800$ mV, $V_D = 500$ mV, $I_{DS0} = 4.3 \mu$A, $\nu = 15.26$ GHz.
microwave field

$V_0$

$v_{dm}$

$v_{sig}$

current amplifier

loop
