Random Telegraph Noise of Deep-Submicrometer MOSFET's

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Abstract—**The random telegraph noise exhibited by deep-submicrometer MOSFET's with very small channel area (≤ 1 μm^2) at room temperature was studied. Analysis of the amplitude of the current fluctuations reveals that the trapped charges generate noise through modulation of the carrier mobility in addition to the carrier number. Parameters needed for modeling the carrier mobility fluctuation effect on the flicker noise in conventional MOSFET's have been extracted directly from the random telegraph noise data.**

I. Introduction

The flicker ($1/f$) noise of metal–oxide–semiconductor field-effect transistors (MOSFET's) has been studied for more than two decades [1]. It is generally agreed that the noise originates from the oxide-trap-induced carrier number and surface mobility fluctuations [2]. However, a quantitative understanding of the noise generation mechanism has not yet emerged. Recently, the availability of deep-submicrometer MOSFET's has provided an opportunity to study the noise generated by individual oxide traps. For MOSFET's with very small channel area (≤ 1 μm^2), it is possible to have only one oxide trap in the vicinity of surface Fermi level over the entire channel. Capture and emission of a carrier by the trap result in discrete modulation of the channel current resembling a random telegraph signal (RTS) [3]. Although considerable effort [3]–[5] has been devoted to the study of the random telegraph noise, most of it has focused on the capture and emission kinetics and very little has been reported concerning the amplitude of the fluctuations. In fact, it is the amplitude of the fluctuations that embodies most of the valuable information critical to a proper modeling of the flicker noise.

II. Theory

Consider an n-channel MOSFET with electrical channel length L_{eff} and width W_{eff}. Capture and emission of a single carrier by an oxide trap will induce *correlated* fluctuations in channel carrier number and mobility. Mathematically,

$$\frac{\Delta I_d}{I_d} = \frac{1}{W_{eff} \times L_{eff}} \left(\frac{1}{N} \frac{\partial N}{\partial N_t} \pm \frac{1}{\mu} \frac{\partial \mu}{\partial N_t} \right) \quad (1)$$

where N_t and N are, respectively, the number of occupied oxide traps and channel carriers per unit area. The sign in front of the mobility term in (1) is chosen according to whether the trap is neutral or charged after the capture of a carrier. A generally accepted model for the carrier mobility is [6]

$$\frac{1}{\mu} = \frac{1}{\mu_0} + \frac{1}{\mu_{ox}} = \frac{1}{\mu_0} + \alpha N_t \quad (2)$$

where μ_{ox} is the mobility limited by oxide charge scattering. It is expected that the scattering coefficient α is a function of carrier density due to the carrier screening effect. Using (2) and recalling that $\partial N / \partial N_t \approx -1$ for $N > 10^{11}$ cm^{-2} [7], (1) can be written as

$$\frac{\Delta I_d}{I_d} = -\frac{1}{W_{eff} \times L_{eff}} \left(\frac{1}{N} \pm \alpha \mu \right). \quad (3)$$

The time in the high-current (ON) state represents the capture time τ_c, whereas the time in the low-current (OFF) state represents the emission time τ_e [3]. It can be shown that the mark–space ratio of the I_d fluctuations is in fact the ratio of the mean capture time to the mean emission time [3]. By detailed balance one has

$$\frac{\langle \tau_c \rangle}{\langle \tau_e \rangle} = g \exp \frac{E_T - E_F}{kT} \quad (4)$$

where g is the trap degeneracy factor and $E_T - E_F$ is the trap energy level relative to the Fermi level. For direct comparison with measurement, (4) can be written as

$$\ln \frac{\langle \tau_c \rangle}{\langle \tau_e \rangle} = K - \frac{q}{kT} \left[\left(1 - \frac{z}{T_{ox}} \right) \Psi_s + \frac{z}{T_{ox}} V_g \right] \quad (5)$$

where T_{ox} is the gate oxide thickness, z is the distance of the trap from the Si–SiO_2 interface (as shown in the inset in Fig. 4), Ψ_s is the surface potential, and K is a constant.

III. Results and Discussions

The deep-submicrometer devices used in this study were fabricated using a photoresist-ashing technique [8]. The gate oxide thickness is 8.6 nm and the substrate doping density is 5×10^{17} cm^{-3}. The threshold voltage is about 1 V. The

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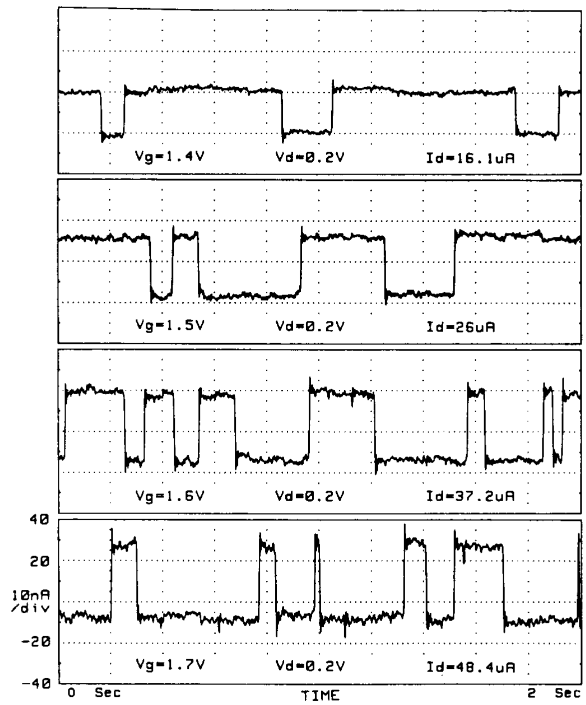

Fig. 1. The fluctuations of drain current at different gate voltages for a deep-submicrometer MOSFET (W_{eff} = 1.2 μm, L_{eff} = 0.35 μm, T_{ox} = 8.6 nm).

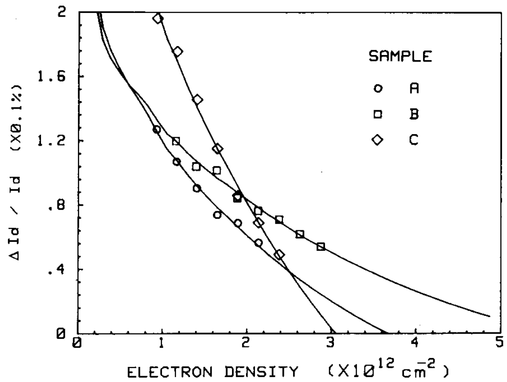

Fig. 2. Plot of $\Delta I_d/I_d$ versus electron density for three different samples. The lines are best fits with (3) and (6). Sample *A* is the same device as in Fig. 1.

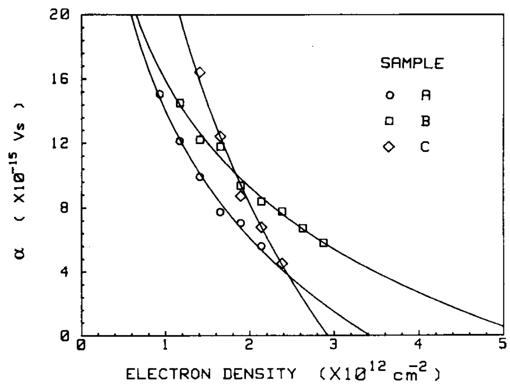

Fig. 3. Plot of the extracted scattering coefficient versus electron density. The lines are best fits with (6).

devices were biased in the linear region ($V_d \leq 0.2$ V) and the drain current fluctuations at room temperature were digitized by a digital spectrum analyzer [9].

Fig. 1 shows the typical current fluctuations of a deep-submicrometer n-MOSFET ($W_{\text{drawn}} = 1.5$ μm, $L_{\text{drawn}} = 1$ μm) measured at different gate biases. For further analysis, we have to determine the effective channel area, surface mobility, and carrier density as functions of the gate bias. The bias dependence of the mobility was extracted from the I_d–V_g characteristics of a large-area MOSFET on the same wafer. The effective channel area $W_{eff} \times L_{eff}$ was estimated by measuring the gate-channel capacitance. Together with the aspect ratio (W_{eff}/L_{eff}) extracted from the I_d–V_g characteristics, both W_{eff} and L_{eff} can be determined. The results for the device in Fig. 1 are $W_{eff} = 1.2$ μm and $L_{eff} = 0.35$ μm. The carrier density was determined by integrating the measured gate-channel capacitance with respect to the gate voltage [10]. The fractional current change for the sample in Fig. 1 is plotted as a function of the carrier density in Fig. 2. Experimental data for two other samples on the same wafer are also shown. The scattering coefficients α extracted from the measured $\Delta I_d/I_d$ are plotted as functions of the carrier density in Fig. 3. The solid lines are best fits with the empirical expression:

$$\alpha = K_1 + K_2 \ln N \tag{6}$$

where K_1 and K_2 are constants. Equation (6) has a functional form resembling the Conwell–Weisskopt formula for a screened coulomb scatterer [11]. This technique is probably the most reliable and direct method to measure the scattering coefficient at the present time. Analyses of RTS's from different devices yield similar magnitude and bias dependence for α. It is interesting to compare the magnitude of α extracted from our RTS data to the value of $\alpha = 2.36 \times 10^{-15}$ V·s used for modeling the oxide charge scattering effect in Sun and Plummer's mobility model [6]. These results confirm that the trapping processes generate noise by modulating the carrier mobility in addition to the carrier number. Equation (3) reveals that the contribution of mobility fluctuations to the noise is proportional to $\alpha\mu$, whereas that of number fluctuations is proportional to N^{-1}. For typical values of $\alpha \approx 10^{-15}$ V·s and $\mu \approx 500$ cm^2·V^{-1}·s^{-1}, these two contributions are comparable to each other in moderate to strong inversion ($N \approx 2 \times 10^{12}$ cm^{-2}). It follows that a proper modeling of the flicker noise in conventional MOSFET's must take into account both number and mobility fluctuations [12].

The bias dependences of the mark–space ratio of the RTS's for the samples under study are shown in Fig. 4. In general, we found that the values of z extracted from different devices may vary from a few angstrom to 20 Å.

IV. Conclusions

We have carried out a detailed study of the random telegraph noise exhibited by deep-submicrometer MOSFET's at

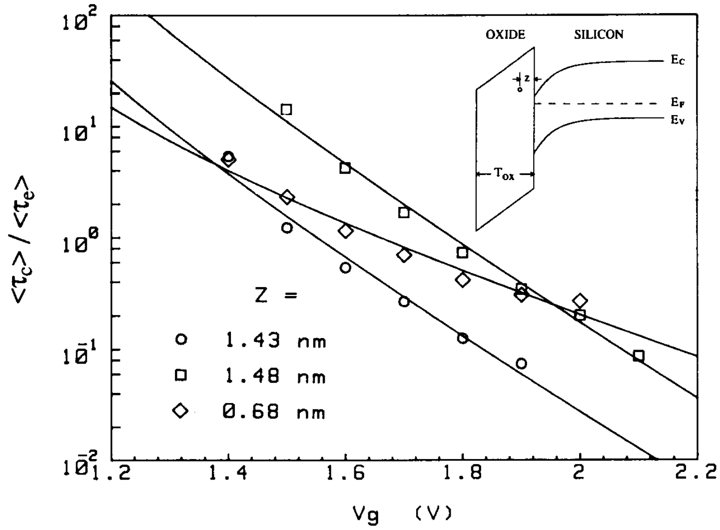

Fig. 4. Plot of the mark–space ratio versus gate bias. The lines are best fits with (5).

room temperature. Analysis of the amplitude of the current fluctuations reveals that the oxide traps generate noise by modulating the carrier mobility in addition to the carrier number. Parameters necessary for modeling the carrier mobility and the mobility fluctuation effect on the flicker noise in conventional MOSFET's have been extracted from the random telegraph noise data.

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