

CURRENT NOISE IN (111) n-CHANNEL Si-MOSFET's AT $T = 4.2$ K

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We have investigated the drain current–drain voltage characteristics and the spectral noise intensity of the drain current of (111) n-channel MOSFET's at $T = 4.2$ K. At $T = 4.2$ K the drain current–drain voltage characteristics showed a hysteresis which was not observed at $T = 77$ K and at room temperature. A qualitative explanation of this hysteresis is given in terms of electron transfer from high mobility valleys to low mobility valleys due to hot electrons. In the spectra of the current noise three contributions could be distinguished: $1/f$ -noise, white noise and generation–recombination noise. The $1/f$ -noise is interpreted as number fluctuations noise. The effective trap density was found to be $2.3 \times 10^{22} \text{ m}^{-3}$. At low drain voltages the white noise can be interpreted as diffusion noise. At higher drain voltages extra noise is observed over and above diffusion noise. This extra noise may be inter-valley noise. The generation–recombination noise was very sensitive to the gate voltage. A tentative explanation can be given if it is assumed that the traps which cause this noise have a non-uniform energy distribution.

1. Introduction

Application of a positive voltage to the gate of an n-channel Si-MOSFET generates an inversion layer at the oxide–semiconductor interface in which the electrons are confined in a potential well with a width of the order of 5 nm. This width is comparable to the de Broglie wavelength of the electrons and therefore quantisation effects occur [1]. The electrons are free to move in the plane of the interface but their motion perpendicular to the interface is quantised. The electrons are grouped in sub-bands and their energy is given by

$$\varepsilon_i(\mathbf{k}) = \varepsilon_i + \frac{\hbar^2}{2} \left(\frac{k_x^2}{m_x} + \frac{k_y^2}{m_y} \right), \quad (1)$$

where the z -direction is chosen perpendicular to the interface. \mathbf{k} is the two-dimensional wavevector of the electrons with components k_x and k_y , m_x and m_y are the effective masses in the x - and y -direction respectively; ε_i is the ground energy

of the i th sub-band, which depends on the effective mass in the z -direction. The energy difference between the sub-bands is of the order of 10 meV [2]. Because of the multi-valley conduction band structure of silicon, more than one sub-band system is generally present. For a (100) surface there are two sub-band systems: a lower system which is two-fold degenerate and originates from the valleys with their large effective mass in the z -direction, and an upper system which is four-fold degenerate (cf. fig. 1). The energy distance between the ground states of these systems is also of the order of 10 meV. For a (111) surface, however, the effective mass along the z -direction is equal for all six valleys. In that case only one six-fold degenerate system exists. The energy separation of the sub-bands in this system is somewhat larger than the separation of the sub-bands in the (100) systems.

Because of the difference in the sub-band structure of the (100)- and the (111)-surface different transport properties can be expected, especially at low temperatures where the thermal

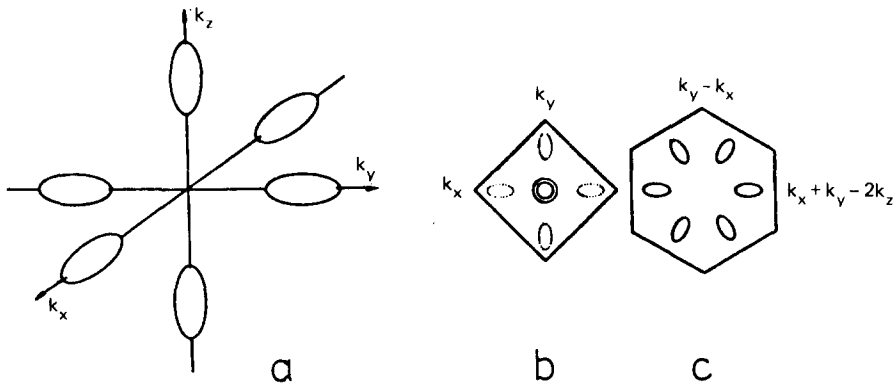


Fig. 1. (a) A schematic diagram of the three-dimensional surfaces of constant energy in k -space for silicon, (b) the two-dimensional Brillouin-zones with contours of constant energy for silicon surfaces with a (100) orientation and (c) with a (111) orientation. Double contours indicate two-fold degeneracy.

energy of the electrons is small compared to the sub-band separation. Recently the current noise of (100) n-channel Si-MOSFET's was investigated at low temperatures [3–5]. In this paper we report experimental results of current noise measurements of (111) n-channel Si-MOSFET's.

In section 2 the devices are described, in section 3 we discuss the drain current–drain voltage characteristics and in section 4 the results of the noise measurements are presented and compared with the results for the (100) n-channel Si-MOSFET's.

2. Devices

The (111) n-channel Si-MOSFET's were grown at the Technical University of Twente, the Netherlands. They have an oxide thickness d of 82 nm and a channel width w of 5 μm . The channel length L was 25 μm or 50 μm . In the following these two types will be referred to as the 25 μm -MOSFET's and the 50 μm -MOSFET's.

The MOSFET's have an Al-gate and a gate protection. The p-type substrate was doped with boron. The concentration of the gate area, calculated with SUPREM II, is 10^{22} m^{-3} . The n^+ source and drain areas are heavily doped with phosphorus and have a concentration of $8 \times 10^{25} \text{ m}^{-3}$, which is large enough to provide ohmic contacts at liquid helium temperatures.

3. Drain current–drain voltage characteristics

In order to investigate the static situation we measured the drain current–drain voltage characteristics and the conductance at zero drain voltage.

The threshold voltage V_T is defined as the minimum gate voltage necessary to induce a conducting channel at the surface of the semiconductor [6]. It is determined from a straight-line extrapolation to zero conductance as a function of gate voltage (cf. fig. 2). A large shift is observed from room temperature ($V_T = 0.4 \text{ V}$) to $T = 4.2 \text{ K}$ ($V_T = 2.7 \text{ V}$). This shift can be ascribed partly to the dependence of the Fermi level on temperature [6, 7] and partly to the existence of interface states near the conduction band edge. The same threshold voltages were found for the 25 μm -MOSFET's as for the 50 μm -MOSFET's. Hot electron effects are described in terms of a field-dependent mobility [8, 9]

$$\mu = \frac{\mu_0}{1 + E/E_c} \quad (2)$$

μ_0 is the low field mobility, E is the magnitude of the electric source-drain field and E_c is the critical field for hot carrier effects.

From the conductance measurements and the threshold voltage the low-field mobility can be calculated using

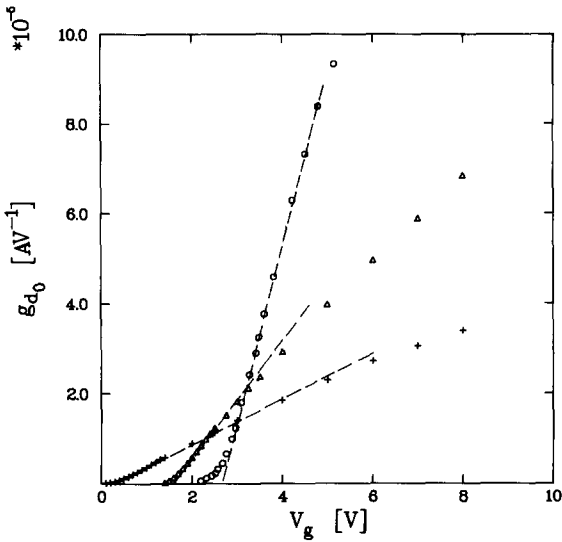


Fig. 2. The conductance at zero drain voltage versus gate voltage at $T = 295$ K (+), $T = 77$ K (Δ) and $T = 4.2$ K (\circ). The threshold voltages are determined by the straight line extrapolations to zero conductance represented by the solid lines.

$$\mu_0 = \frac{g_{d0} L}{w C_{ox} (V_g - V_T)} \quad (3)$$

g_{d0} is the conductance at zero drain voltage and C_{ox} is the oxide capacitance per unit area.

At $T = 4.2$ K μ_0 was found to be of the order of $0.5 \text{ m}^2/\text{Vs}$. The critical field can in principle be extracted from the $I_d - V_d$ characteristics. However, when we measured the characteristics at $T = 4.2$ K, hysteresis effects were observed (cf. fig. 3). The curve obtained by increasing the drain voltage was systematically somewhat higher than that obtained by subsequently decreasing the drain voltage. These hysteresis effects were not observed at $T = 77$ K or at room temperature. The magnitude of the hysteresis depends on the rate of changing the drain voltage, but even at a rate of 3 mV/s shifts of more than 10% were found. Moreover, at a fixed drain voltage the drain current varies slowly for several hours. These effects made it impossible to determine quantitatively the critical fields in terms of which hot carrier effects can be described. However, we believe that the hysteresis can be understood qualitatively in terms of a transferred-electron

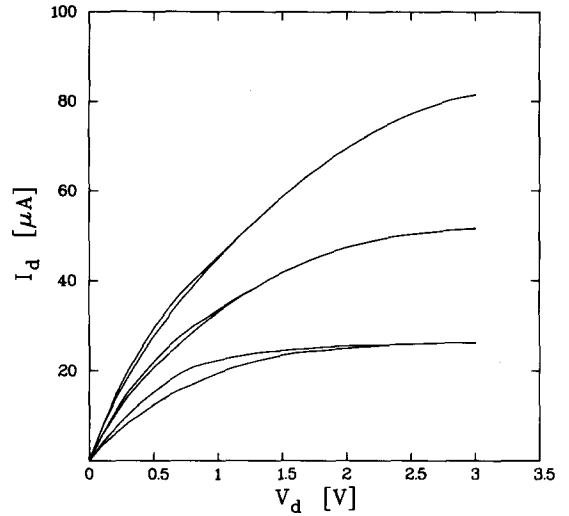


Fig. 3. $I_d - V_d$ characteristics measured at $T = 4.2$ K, showing hysteresis effects. The upper curves are obtained by increasing the drain voltage, the lower curves by decreasing the drain voltage.

effect [6]. Although in a (111) plane the six valleys are equivalent as far as the energy is concerned, they split up into at least two groups of valleys with different mobilities when an electric field is applied along an axis in the (111) plane. If the electric field is increased sufficiently the electrons in the high mobility valleys heat up and are transferred to the low mobility valleys [10–12]. Since quite a large change in crystal momentum is involved this transfer can only take place if an energetic phonon is absorbed or emitted. The absorption of an energetic phonon is very unlikely at low temperatures since there are very few energetic phonons available. However, the electrons in the high mobility valleys can emit an energetic phonon because they have been heated up by the electric field. The reverse transfer process, which will take place if the electric field decreases, is much slower since the electrons in the low mobility valleys are much colder, giving rise to hysteresis, as observed.

4. Noise measurements

The devices were used with AC-shortened gates and are essentially one-port with the source- and

drain-contacts as terminals. The spectral noise intensity of the drain current was measured as a function of gate voltage at low drain voltages ($V_d \ll V_g - V_T$) and as a function of drain voltage at fixed gate voltages. The frequency range covered was 1 Hz to 300 kHz. The temperature was kept at $T = 4.2$ K. The data were collected after we had waited a considerable time for a stationary state to be reached. A detailed description of the experimental set-up and the experimental procedure is given elsewhere [5].

In most of the spectra a $1/f^\beta$ component, a Lorentzian and a white noise component could be distinguished. Some spectra of the $25 \mu\text{m}$ -MOSFET's showed a second Lorentzian. A typical result is given in fig. 4.

Therefore the spectra were fitted to the following equation:

$$S_{I_d}(f) = \frac{S_{(1/f)}(100)}{(f/100)^\beta} + \frac{C^I}{1 + (2\pi f\tau_1)^2} + \frac{C^{II}}{1 + (2\pi f\tau_2)^2} + C^{III}. \quad (4)$$

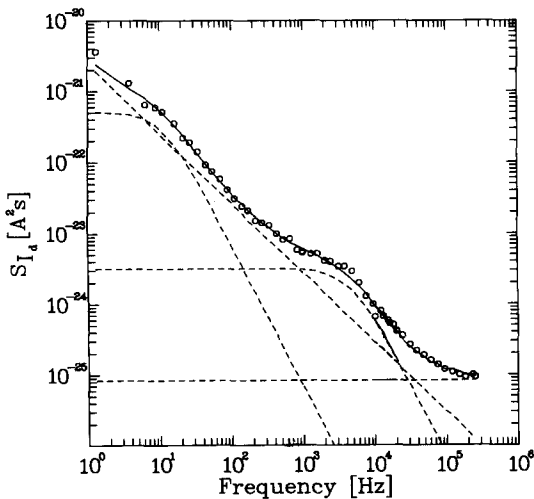


Fig. 4. A typical result of the spectral noise intensity of the drain current versus frequency at $T = 4.2$ K, $V_g = 10$ V, $V_d = 0.05$ V and $I_d = 7.9 \mu\text{A}$. The open circles represent the experimental data. The solid line represents the sum of the $1/f$ -noise, the white noise and the Lorentzians. The latter are indicated by dashed lines and are obtained by computer analysis.

The third term on the right-hand side is optional. $S_{1/f}(100)$, β , C^I , C^{II} , C^{III} , τ_1 and τ_2 are fitting parameters to be obtained from a computer fit.

In the next sections we shall discuss in succession the results for the white noise, the $1/f$ -noise and the Lorentzians.

4.1. White noise

In fig. 5 we have plotted the white noise versus drain voltage at $V_g = 5.8$ V and $V_g = 8.0$ V for the $50 \mu\text{m}$ -MOSFET's and at $V_g = 8.0$ V for the $25 \mu\text{m}$ -MOSFET's. The white noise of the $25 \mu\text{m}$ -MOSFET's could only be distinguished clearly at drain voltages of less than 0.1 V. At higher drain voltages it was masked by other noise contributions.

At $V_d \ll V_g - V_T$ the white noise can be interpreted as diffusion noise which can be approximated by $4kTI_d/V_d$. At higher drain voltages extra noise is observed over and above diffusion noise. The literature mentioned several possible explanations for this extra noise: a generation-recombination process between the conduction band and impurities in the forbidden band, generation-recombination processes between the conduction band and localised states around the Fermi level, impact ionisation by hot carriers and

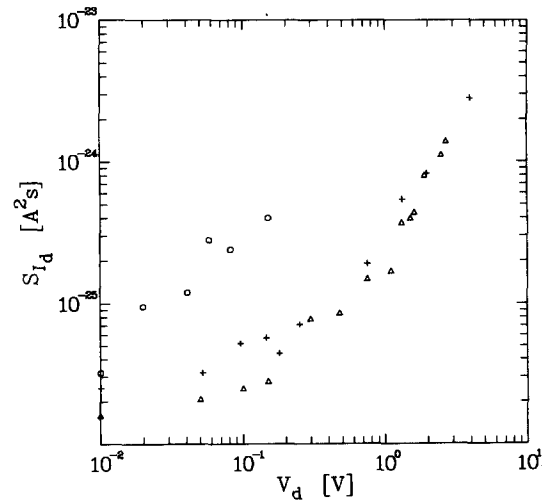


Fig. 5. The white noise versus drain voltage at $T = 4.2$ K for the $50 \mu\text{m}$ -MOSFET's at $V_g = 5.8$ V (Δ) and $V_g = 8.0$ V ($+$) and for the $25 \mu\text{m}$ -MOSFET's at $V_g = 8.0$ V (\circ).

inter-valley noise. As in the case of the (100) n-channel MOSFET's [4, 5] we opted for the explanation based on inter-valley noise. Generation-recombination processes between the conduction band and impurities in the forbidden band are highly unlikely since the 2D-electron gas is degenerate and the thermal energy of the electrons is much smaller than the energy of the impurities with respect to the Fermi level. Impact ionisation should have a breakthrough effect on the I_d - V_d characteristics, but this was not observed. Generation-recombination noise due to localised states around the Fermi level cannot be ruled out. However, if present we expect it to be sensitive to the position of the Fermi level which is determined by the gate voltage. This was not found. Therefore we interpret the extra noise as inter-valley noise. Fluctuations in the rate of transitions between the low mobility valleys and the high mobility valleys will give rise to fluctuations of the drain current. These fluctuations can be described as a generation-recombination process which has a Lorentz spectrum. In the frequency range investigated we only measured the plateau value of the Lorentzian, which means that the noise relaxation time is less than 10^{-6} s. Therefore the observed inter-valley noise cannot be due to transitions between the ground states of the low mobility valleys and the high mobility valleys which will have a larger relaxation time. Probably the inter-valley noise is caused by fluctuations in the rate of transitions from the ground state of the high mobility valleys to the first excited sub-band of the low mobility valleys or to the first excited sub-band of the high mobility valleys, provided that the mobility of the electrons in this sub-band differs from the mobility of the electrons in the ground state. The difference in the energy of these states is comparable to that of the ground states of the upper and lower valleys in the (100) plane. Transitions between the latter states are responsible for the observed inter-valley noise of the (100) n-channel MOSFET's.

4.2. $1/f$ -noise

In fig. 6 we have plotted $I_d^2/S_{1/f}(100)$ versus

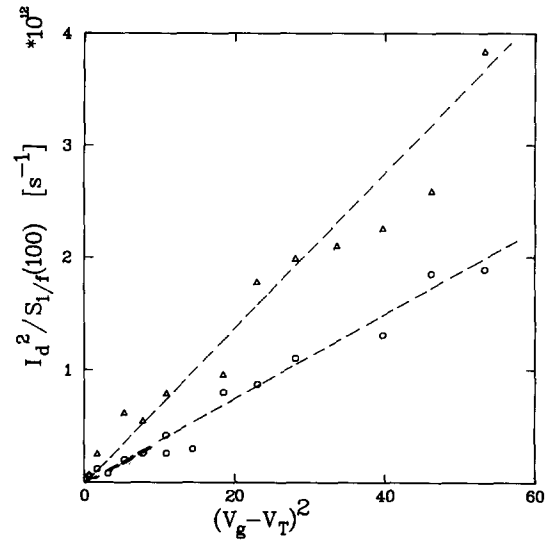


Fig. 6. $I_d^2/S_{1/f}(100)$ versus $(V_g - V_T)^2$ at $T = 4.2$ K and low drain voltages. The circles and the triangles represent the data for the $25 \mu\text{m}$ -MOSFET's and the $50 \mu\text{m}$ -MOSFET's respectively. The dashed lines represent the fit of eq. (6) to the experimental data.

$(V_g - V_T)^2$ at low drain voltages ($V_d \ll V_g - V_T$). The graph shows that $I_d^2/S_{1/f}(100)$ is proportional to $(V_g - V_T)^2$.

There are two major models explaining the $1/f$ -noise: the number fluctuations model [13] and the mobility fluctuations model [14]. In the latter it is assumed that the relative spectral $1/f$ -noise intensity of a homogeneous semiconductor operated in the ohmic regime is inversely proportional to the number of free electrons. At low drain voltages the number of free electrons is approximately equal to $wLC_{ox}(V_g - V_T)/q$. Then it follows that [15]

$$\frac{I_d^2}{S_{1/f}} = \frac{fwLC_{ox}}{\alpha_H q} (V_g - V_T). \quad (5)$$

α_H is the Hooge-parameter. This expression holds also for number fluctuations if it is assumed that the effective trap density at the Fermi level is proportional to $(V_g - V_T)$ [16]. α_H is then related to the effective number of traps at the Fermi level. However, if the trap density N_T is independent of energy the following expression can be derived [15, 17]:

$$\frac{I_d^2}{S_{1/f}} = \frac{f\omega LC_{ox}^2 \gamma}{q^2 N_{T_{eff}}} (V_g - V_T)^2. \quad (6)$$

$N_{T_{eff}}$ is the effective trap density at the Fermi level and is equal to kTN_T . γ is a tunnelling parameter of the order of 10^{10} m^{-1} .

From a comparison of eq. (5) and eq. (6) with the experimental results we conclude that the $1/f$ -noise in the (111) n-channel MOSFET's is caused by number fluctuations. The trap density, at least around the Fermi level, is independent of energy.

From the slopes of the straight lines in fig. 6 the effective trap density can be calculated:

$$N_{T_{eff}} = (2.4 \pm 0.5)10^{22} \text{ m}^{-3}, \quad (L = 50 \mu\text{m});$$

$$N_{T_{eff}} = (2.2 \pm 0.3)10^{22} \text{ m}^{-3}, \quad (L = 25 \mu\text{m}).$$

These trap densities are an order of magnitude larger than the trap densities obtained for the (100) n-channel MOSFET's at $T = 4.2 \text{ K}$ if the $1/f$ -noise of the latter is interpreted as number fluctuations noise. This is in agreement with measurements of the trap density by other techniques in which generally higher values are found for the (111) orientation [18, 19, 20, 21]. Difference in processing techniques can also lead to different trap densities [22].

In fig. 7 we have plotted the $1/f$ -noise at $f = 100 \text{ Hz}$ and $V_g = 8 \text{ V}$ versus $I_d V_d$ for the $25 \mu\text{m}$ -MOSFET's. The $1/f$ -noise first increases proportionally to $I_d V_d$, then levels off, and subsequently it increases again proportionally to $I_d V_d$. Similar results are obtained for the $50 \mu\text{m}$ -MOSFET's.

This behaviour can be understood qualitatively in terms of $1/f$ -noise in different valleys. At low electric fields, when no hot electrons are present, the spectral $1/f$ -noise intensity of the drain current is proportional to $I_d V_d$ [23]. If the energy distribution of the traps is uniform it is given by [15]

$$S_{1/f} = \frac{q^2 \mu N_{T_{eff}} I_d V_d}{fL^2 \gamma C_{ox} (V_g - V_T)}. \quad (7)$$

The electrons are distributed among the low

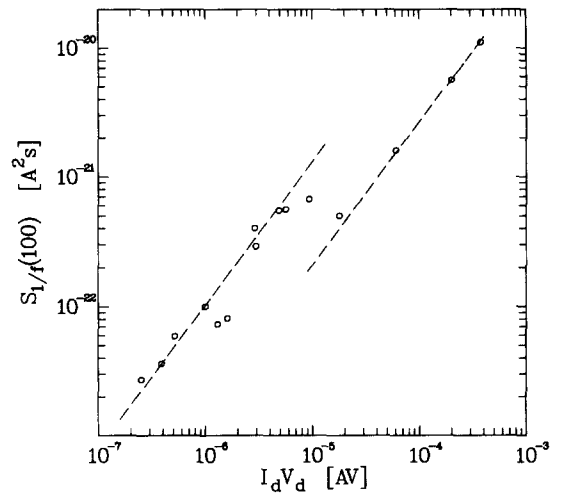


Fig. 7. The $1/f$ -noise at $f = 100 \text{ Hz}$ versus $I_d V_d$ for the $25 \mu\text{m}$ -MOSFET's at $V_g = 8.0 \text{ V}$ and $T = 4.2 \text{ K}$. The dashed lines are drawn to show the proportionality between the $1/f$ -noise and $I_d V_d$ at low and high fields.

mobility valleys and the high mobility valleys. If the electric field increases, the electrons first heat up in the high mobility valleys and are transferred to the low mobility valleys. Due to hot electron effects the $1/f$ -noise in the high mobility valleys increases more slowly and the total $1/f$ -noise levels off. At high electric fields most of the electrons are in the low mobility valleys and the contribution of high mobility valleys to the $1/f$ -noise can be neglected. Only the $1/f$ -noise in the low mobility valleys is left over and apparently this noise is not affected by hot electrons in the range of the electric fields applied, since the measured $1/f$ -noise is again proportional to $I_d V_d$.

4.3. Generation-recombination noise

In most of the spectra one or two Lorentzians were observed. These Lorentzians can be ascribed to fluctuations in the number of electrons. Free electrons can be temporarily trapped in so called trapping centres and trapped electrons can be temporarily added to the number of free electrons. If the electron gas is in thermodynamic equilibrium the spectral intensity of the fluctuations in the number of carriers in an element Δx of the channel for a single-energy-level

trap is given by [24]

$$S_N(f) = \frac{4N_{t_0}f_t(1-f_t)}{\Delta x[1+(2\pi f\tau)^2]} \quad (8)$$

τ is the noise relaxation time, N_{t_0} is the number of traps per unit of length and f_t is the Fermi-Dirac distribution function. If the channel is outside thermodynamic equilibrium one can define a quasi-Fermi level for each band assuming that intra-band transitions are very rapid with respect to noise relaxation processes. It was shown that the spectrum of the fluctuations in the drain current due to such a generation-recombination process is also a Lorentzian [25], even in the case of field-induced transitions [26]. In the latter case the rate of transitions depends on the electric field and as a consequence the relaxation time of Lorentzians depends on drain voltage.

In fig. 8a we have plotted τ versus V_d at $V_g = 8.0$ V for the 50 μm -MOSFET's. In fig. 8b the corresponding ratio $S_{I_d}(0)/\tau$ is plotted versus I_dV_d . As expected from simple g-r theory $S_{I_d}(0)/\tau$ is proportional to I_dV_d [27]. However τ decreases with increasing drain voltage. Apparently the generation-recombination is field induced.

In fig. 9a and fig. 9b we have plotted τ and $S_{I_d}(0)/\tau$ versus gate voltage at low drain voltage and $I_dV_d = 0.8 \mu\text{W}$ for the 25 μm -MOSFET's. Although $V_g - V_T$ changes by less than a factor

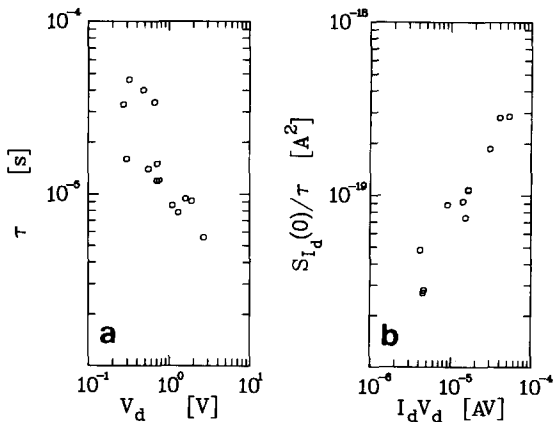


Fig. 8. (a) τ versus V_d and (b) $S_{I_d}(0)/\tau$ versus I_dV_d at $T = 4.2$ K and $V_g = 8.0$ V for the 50 μm -MOSFET's.

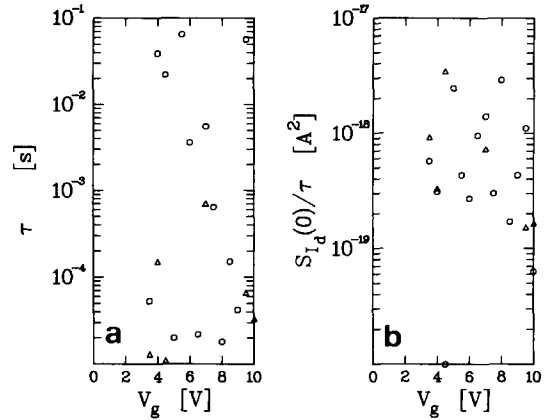


Fig. 9. (a) τ versus V_g and (b) $S_{I_d}(0)/\tau$ versus V_g at $T = 4.2$ K for the 25 μm -MOSFET's. The triangles represent the data of the second Lorentzian, if two Lorentzians were observed. $I_dV_d = 0.8 \mu\text{W}$.

10, $S_{I_d}(0)/\tau$ varies over two orders of magnitude and the variation of τ is even more dramatic. Apparently the g-r noise is very sensitive to the gate voltage.

A tentative explanation can be found in a non-uniform energy distribution of the traps which cause the g-r noise. From the term $f_t(1-f_t)$ it is clear that only traps which have an energy of the order of kT with respect to the Fermi level can contribute to the noise. At liquid helium temperature $kT = 0.4$ meV. The change of the Fermi level is of the order of 15 meV if the gate voltage changes from 3.5 V to 10 V. If the variation of the energy distribution of the traps is on a scale of the order of kT the noise will be very sensitive to the position of the Fermi level and as a consequence to the gate voltage. If the Fermi level is in a local maximum of the trap density, the net effective traps which contribute to the noise will be larger than while the Fermi level is in a local minimum.

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