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Effect of gamma radiation treatment on transport properties of silicon nanowire field effect transistors

Here we report on silicon nanowire (NW) field effect transistor (FET) structures fabricated and their transport properties studied before and after gamma radiation treatment. I-V characteristics and noise spectra of Si NW FETs of different lengths demonstrate improvement of stability and scaling after irradiation treatment. The results are interpreted as strain relaxation in contact regions as well as changes of the charge state of dielectric traps after the influence of low doses of gamma irradiation. This approach is promising for nanoelectronic applications, including biosensors.

Keywords: nanowires, silicon, field effect transistors, noise spectroscopy, gamma radiation treatment.

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Вплив гамма радіації на транспортні властивості польових транзисторів на базі кремнієвих нанониток

Представлено результати по виготовленню та подальшому дослідженню електрофізичних властивостей польових транзисторів на базі кремнієвих нанониток до та після обробки малими дозами гамма радіації. Виміряні вольт-амперні характеристики показують покращення стабільності та відтворюваності після обробки радіацією. Зміни у транспорті під дією малих доз гамма опромінення інтерпретовано, як релаксацію механічних напружень в контактних областях транзисторів, а також як зміну зарядових станів пасток в затворному діелектрику. Розроблений пібхід є багатообіцяючим для застосувань в наноелектроніці, включаючи біосенсорні застосування.

Ключові слова: нанонитки, кремній, польовий транзистор, шумова спектроскопія, опроміннення гамма радіацією.

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Introduction

Novel test structures fabricated on the basis of Si nanowires are the ultimate building blocks for future nanoelectronics[1] and biological sensor applications [2]. These structures should be stable in operation. However, a great many factors influence their reliability and stability of such devices, especially in the nanowire channel. One of the factors is the stress effect in oxidized Si nanowires[3]. Also the degradation processes in nanochannel FETs are very large compared with negligible degradation for conventional MOSFETs[4]. The measured I-V characteristics of poly-Si FETs demonstrate Joule heating degradation of the structures[5]. In addition, hot carriers may generate the interface traps resulting in degradation of the FET threshold voltage [6]. It has already been demonstrated that Si nanowire structure performance is related to the microstructure of ohmic contacts to NWs[7].

In this paper, we report on the transport and noise properties of silicon nanowire field effect transistors with different channel lengths. We applied low-dose gamma irradiation treatment to the samples to obtain improved contact regions and more stable and reproducible operation of the test device structures.

Experimental details

The structures under study were fabricated on the basis of SOI wafers with a 150 nm buried oxide (BOX) layer using nanoimprint technology. The thickness of Si layer (Si<100>, boron-doped 14–22 Ohm*cm) was 50 nm with p-type doping of $2x10^{15} cm^{-3}$. High-quality nanowires with low defect density were obtained by tetramethylammonium hydroxide (TMAH) chemical wet etching. The lengths of the fabricated devices varied from 2µm to 16 µm with widths of 250 nm. A scanning electron microscope (SEM) image of one of the nanowire is shown in Fig.1. Si contact pads were doped by ion implantation of As atoms with an energy of 8 keV, dose $5x10^{14}$ cm^{-2}, and were subsequently annealed at 950°C for 30 sec in nitrogen atmosphere to activate the implanted ions and improve the electrical performance of the devices. A thin SiO_2 dielectric layer with a thickness of 100nm was thermally grown to achieve stable surface passivation of Si NWs. The conductivity of the samples was modified by applying a voltage to the substrate used as the gate electrode.

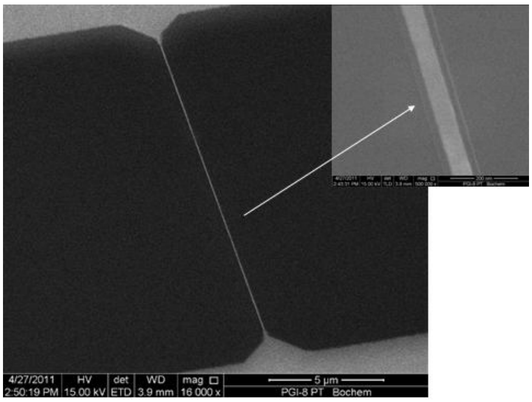


Fig. 1 Scanning electron microscope image of fabricated silicon nanowire. Scale bar is 5 µm. Insert: enlarged image of the NW with width of 250 nm.

Characterization of Si NW FETs

The electrical properties of the back-gated nanowire FETs were studied using I-V characteristics and low-frequency noise spectra measurements at room temperature. A low-noise noise measurement setup was developed in-house based on an amplifier with a low level of intrinsic input-related thermal noise of $2x10^{-18}$ V^2Hz^{-1}, which enables the peculiarities of noise spectra to be studied in the frequency range from 1 Hz to 100 kHz and the characteristic parameters of the structures to be extracted as a function of channel length. Transfer characteristics of the Si NW devices of different lengths are shown in Fig. 2. A characteristic feature of these samples is a slow drift (decrease) of the drain current when drain-source voltage,V_{DS}, is applied during long time about two hours. Transfer characteristics registered in the short-time regime (5 minutes after applying the voltage) and after a longer period (2 hours) differ. In the second case, the measurements were performed after the establishment of the quasi-steady state. In spite of a decrease in current in the steady-state regime, there was no change registered in the threshold voltage V_{th}, determined as: – 1.26 V

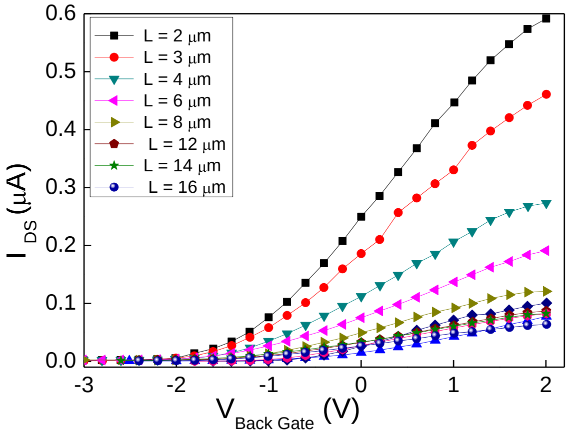


Fig. 2 Transfer characteristics measured for Si NW FETs of different lengths,listed in the figure, at V_{DS} = 100 mV.

In addition, at negative gate voltages a significant uncontrolled subthreshold current was registered. This current has a tendency to increase with increasing of negative voltages V_{BG} from -2 to -3 V. The dependence of the resistance of the samples on length demonstrates a good enough scalability with length, except for the samples of the smallest lengths, where we found that the contact resistance should be taken into account.

Noise measurements of samples of different lengths showed that the spectra mostly demonstrate *1/f* behavior. A study of noise as a function of gate voltage showed that the main source of noise is the exchange process of the carriers with traps in the dielectric layer. This process can be described by the McWhorter model. The input-related noise spectral density is usually used to analyze the noise properties of the structures. Such equivalent input noise voltage at the gate was determined in accordance with the following expression:

$$S_U = \frac{S_I}{g_m^2} \tag{1}$$

where S_I is the current channel noise, gm is the transistor transconductance, which can be determined from the slope of the transfer characteristic of the transistor using the following expression:

$$g_m = \frac{\partial I_{DS}}{\partial V_{BG}} \tag{2}$$

However, in some cases well-resolved Lorentzian noise components were registered in the spectra above the flicker noise. The Lorentzians were observed in the spectra of short samples at high gate voltages. Typical families of spectra measured for samples with a length of 2 μm length are shown in Fig. 3. The roll-off of the spectrum at f > 3 kHz is due to the input capacitance of the low-noise amplifier with a large equivalent resistance of the circuit (R_{eq} = 100 kOhm), therefore f_{cutoff}= $1/RC$ is about 3 kHz.

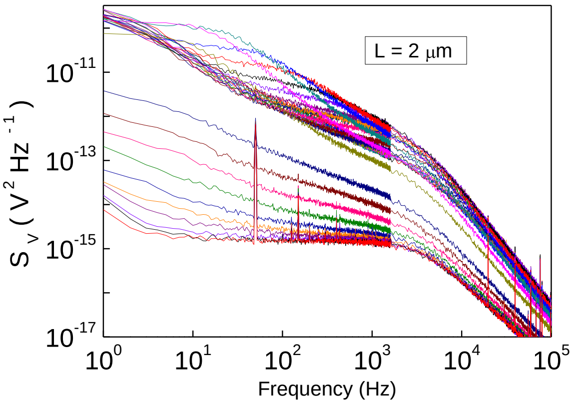


Fig. 3. Measured noise spectral density for Si NW FET sample of length L = 2 μm at gate voltages from 2V to -2V.

The 1/f noise level at the frequency of f = 1 Hz is selected as the parameter. The dependence of this parameter on the gate voltage is used to obtain the input-related noise spectral density, S_U , as a function of V_G, shown in Fig.4.

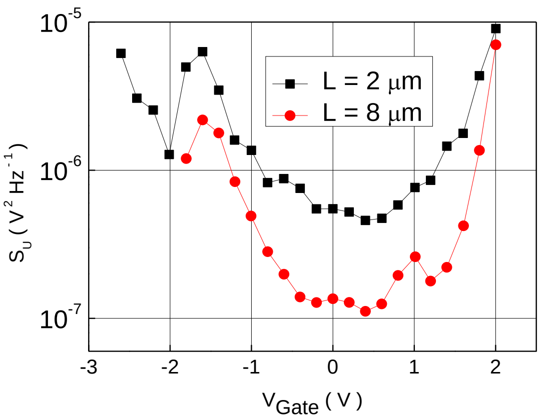


Fig. 4. The input-related noise spectral density, SU , as a function of V_{BG}, obtained for Si NW FETs of different lengths.

These dependences are typical of metal oxide semiconductor field effect transistor (MOSFET) structures. A weak dependence is observed in the accumulation regime at high voltages and a sharp decrease in the subthreshold regime.

The fact that the observed dependence has a flat region confirms the applicability of the McWhorter model in this case, where:

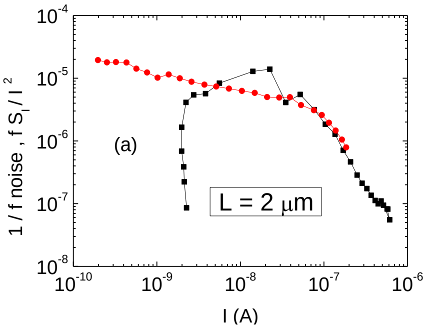
$$S_U(f) = \frac{kTq^2\lambda N_{ot}(E_F)}{fWLC_0^2} \sim \frac{1}{WL}, \qquad (3)$$

where $N_{ot}(E_F)$ – trap density in the dielectric, C_0 = ε_{ox}/t_{ox} is the gate insulator capacitance per unit area, ε_{ox} is the permittivity of the dielectric layer, t_{ox} is the oxide thickness, $\lambda = \sqrt{\hbar^2/2m_z^*\phi_B}$ =10^{-8} is the tunneling distance, W is the width of the sample.
Using (3) we can determine the density of active sites in the lower dielectric, substituting the ε_{ox} = 3.9 ε_0 and t_{ox} = 150 nm, S_U = 10^{-7}, L = 10 μm, W = 0.25 μm: N_{ot} is about $5\text{x}10^{17}$ $cm^{-3}eV^{-1}$. This value is not as high as that obtained for high-quality bulk Si material [8].

Electric properties of Si NW FETs before and after gamma radiation treatment

Typical noise characteristics of Si NW FETS measured before and after gamma radiation treatment using ^{60}Co are shown in Fig.5.The measurements were performed in the linear regime at V_{DS} = 100 mV for samples with the same width of 250 nm and different lengths. Decreased scattering in the structure characteristics is found after treatment. The characteristic behavior of structures differs for short and long samples.

In the strong inversion (high currents) in the samples before irradiation (lengths L = 2 μm and 8 μm) and in the sample of length L = 2 μm after irradiation, the dependence of the noise on the current follows S_I/I^2 ~ $1/I^2$. At the same time, in a sample of length L = 8 μm after irradiation the behavior is different and the normalized current density follows S_I/I^2 ~ $1/I$ and is proportional to the inverse current. The first dependence is typical of the noise determined by the near-contact region, the second is characteristic of noise related to channel transport. It is obvious that in a short sample the influence and contribution of contacts into the noise properties of the samples is higher than in the case of long samples. Thus in the case of short samples in the strong inversion mainly the noise related to near-contact regions was registered and the noise related to the channel phenomena was registered in the case of long samples before and after irradiation. After gamma radiation treatment, the contact contribution became negligible and the noise results for short-channel samples also showed channel-related properties.



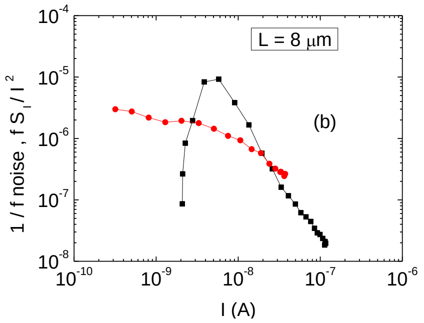


Fig. 5. Normalized current spectral density of 1/f noise component, measured for the sample with length of 2 μm (a) and 8 μm (b) before irradiation (black circles) and after irradiation (red circles).

Irradiation leads to the removal of mechanical stress in the contact region, which also reduces 1/f noises. In addition, normalized flicker noise demonstrates different length dependences for samples with short lengths (Fig.6) before and after irradiation.

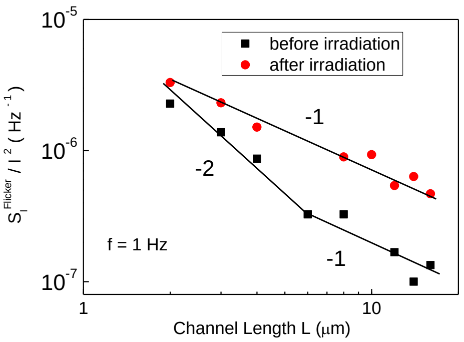


Fig. 6. Normalized current spectral density of the flicker noise component versus sample length, V_{DS}=100 mV and V_G-V_{th}=0.5 V.

We have found that the normalized current noise spectral density decreases as $1/L^2$ in the samples with lengths of less than 7μm. Such dependence is characteristic for the major contact contribution to the noise properties. At the same time, in relatively long samples the behaviour changed to *1/L* dependence, demonstrating the priority of channel noise. The latter dependence was also registered for samples with small lengths after gamma irradiation, reflecting the positive effect of the irradiation due to stress relaxation in the contact regions [9] as well as increased stability of the structures and decreased scattering in the characteristics. The results demonstrate the positive effect of irradiation on the stability and reliability of the structure parameters.

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