Low-frequency noise in single electron tunneling transistor

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The noise in current biased aluminium single electron tunneling (SET) transistors has been investigated in the frequency range of 5 mHz$<f<$30 Hz. A refined high frequency (HF) shielding including resistive coaxial lines, that prevents spurious electromagnetic radiation and especially high energy photons emitted by the 4.2 K environment from reaching the sample, allows us to study a given background charge configuration for many hours below $\approx$100 mK. The noise at relatively high frequencies originates from internal (presumably thermal equilibrium) charge fluctuations. For $f \geqslant 10$ Hz, we find the same input charge noise, typically $Q_N = 5\times 10^{-4}$ e/Hz$^{1/2}$ at 10 Hz, with and without the HF shielding. At lower frequencies, the noise is due to charge trapping, and the voltage noise pattern superimposed on the $V(V_g)$ curve (voltage across transistor versus gate voltage) strongly depends on the background charge configuration resulting from the cooling sequence and eventual radio frequency (rf) irradiation. The measured noise spectra which show both $1/f$ and $1/f^{1/2}$ dependencies and saturation for $f<100$ mHz can be fitted by two-level fluctuators with Debye–Lorentzian spectra and relaxation times of order seconds. In some cases, the positive and negative slopes of the $V(V_g)$ curve have different overlaid noise patterns. For fixed bias on both slopes, we measure the same noise spectrum, and believe that the asymmetric noise is due to dynamic charge trapping near or inside one of the junctions induced when ramping the junction voltage. Dynamic trapping may limit the high frequency applications of the SET transistor. Also reported on are the effects of rf irradiation and the dependence of the SET transistor noise on bias voltage. [S0021-8979(98)06301-4]

I. INTRODUCTION

Single electron tunneling (SET) devices are considered as potential candidates for future high density electronics because of their unique properties such as very low power operation and subelectron charge sensitivity (see Ref. 1 for review). Their long term stability and general noise properties when integrated in real circuits are of crucial importance in most SET applications such as electrometers, charge amplifiers, electron traps, and current standards (see Refs. 2–5 and references therein). The basic three-terminal component is the SET transistor which consists of two nearly identical series connected ultrasmall high-resistance tunnel junctions with capacitance $C_1 \approx C_2 \ll e^2/k_BT$ and resistance $R_1 \approx R_2 \gg R_Q = h/e^2$. The charge of the interconnecting metallic island can be regulated continuously by applying a voltage V_g to a gate electrode which is capacitively coupled to the island by a small gate capacitance $C_g < C_1, C_2$. If the total capacitance $C_\Sigma = C_1 + C_2 + C_g$ of the island is so small that admission of one electron, giving the additional charging energy $E_C = e^2/2C_\Sigma$, changes its electrostatic energy significantly, the system shows so-called Coulomb blockade. With a dc bias voltage V applied across the transistor the quantized tunnel current of single electrons becomes e periodic with the period $C_gV_g = e$, and in the ideal case ($T=0$, orthodox theory Ref. 1), the current may be reduced to zero for $V \leqslant V_C = e/C_\Sigma$; the Coulomb blockade threshold. In real SET, transistors both noise and cotunneling[6] prevent full blockade, and the bias condition determines which of the two junctions mainly limits the tunnel current.

Most metal SET devices are Al/Al_2O_3/Al tunnel junctions fabricated by shadow evaporation with masks made by electron beam lithography. This technique only allows for production of junctions with capacitance down to $\approx$10 aF implying that operational temperatures need to be in the millikelvin range. Other materials,[7,8] fabrication techniques (see Ref. 2 for review also on semiconductor based junctions), and structures[9] are being developed. Recently junctions with capacitance as low as $C \approx 0.1$ aF, showing Coulomb blockade and Coulomb staircase at room temperature, have been fabricated by nano-oxidation of a Ti film using the tip of a scanning tunneling microscope (STM).[10]

The major obstacle to future applications of the SET transistor is fluctuations in the excess charge on the island leading to a high level of $1/f^\alpha$ type noise which at low frequencies dominates other intrinsic noise sources such as shot noise and resistance fluctuations. Current or voltage noise with $1/f^\alpha$ (α between 0.5–1.5) frequency dependent noise has been observed in almost all electronic devices, each having a characteristic frequency range and spectral density. According to Hooge's empirical law,[11] the spectral density varies inversely with the total number of carriers in the system. Except for a few systems, the physical origin of the $1/f^\alpha$ noise is not understood and in most cases it is not even clear whether it is a volume or a surface effect. Theoretical models based on surface trapping and equilibrium thermal energy exchange with the environment have been extensively discussed. For the SET transistors, the random pulse train model is of particular interest due to the experimental obser-

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