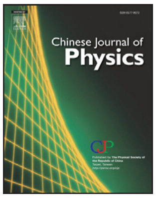
Chinese Journal of Physics 55 (2017) 1225–1229

Contents lists available at ScienceDirect

Chinese Journal of Physics

journal homepage: www.elsevier.com/locate/cjph



Study of electron charging by voltage pulses in nanopillar transistors at high temperature

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ARTICLE INFO

Article history:
Received 10 December 2016
Revised 7 May 2017
Accepted 22 May 2017
Available online 29 June 2017

Keywords:
Quantum dot
Nanopillar transistor
Pulsed voltage
Mechanical vibration
Room temperature

ABSTRACT

A study of electron transport in nanopillar transistors at 300 K shows that elastic vibration is an intrinsic behavior of the device. The frequency observed in the drain-source current is found to agree with that of the charging pulsed voltages. Given a quantum dot of size $10 \times 10 \times 9\,\text{nm}^3$, the maximum displacement is estimated to be 0.3 nm. Once the displacement diminishes to zero, single-electron tunneling becomes the dominant effect. A forced vibration model is proposed to explain the correlation between the surface charges and the vibrations. When the distribution of charges is uniform on each SiNx atom, the vibration becomes stable and can yield a homogenous damping current.

Research in electron transport of mechanical quantum dot transistors [1–4] has made tremendous progress in the last two decades. No doubt it is one of the most fascinating topics for physicists, because it has the potential to revolutionize modern technology in semiconductors. It also provides challenges for theoretical understanding in the field. The discovery of single electron tunneling is a hallmark effect, because it has been incorporated into devices, such as the single-electron pump [5], single-electron memory cell [6], and single-electron detector and counter [7]. In addition to these devices, we have also presented the vertical "nanopillar" transistor [8]. In this device, drain current versus drain-source voltage measurements at room temperature show excellent features associated with single-electron peaks. By matching the peak spacing with the parallel plate charging energy $Ec = e^2/2C$, a single electron tunnel is then confirmed.

However, a critical issue remains unanswered in that paper, which is why the onset of peaks is always at a finite voltage. Early I-V measurements at low temperatures [9–11] had found the same kind of effect, and it was attributed to a Coulomb blockade, where all the charges are totally repelled by the Coulomb interaction and no current could flow. But lately, the concept of a quantum shuttle [12] has been proposed to explain how electrons can move from one electrode to another via the repetitive motion of the central dot at finite temperatures. Consequently, current noise [13] will appear. In our view, in this highly uncertain region other mechanisms, such as dissipation [14], elastic deformation [15], and mechanical feedback [16] can also play a vital role. As such, it is definitely worth doing more careful experiments in this subject. As is expected, we find that at very low charging voltages, the I_d-V_d curve shows drastically different behavior compared to what has been observed before; giant oscillations appear and dominate the I-V spectrum from the very beginning. After reaching a maximum value the current quickly decreases to zero. Thereafter, periodic peaks show up again. To understand this unprecedented phenomena, we proposed a forced vibration model. It turns out that this model can explain the observed data very well.

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http://dx.doi.org/10.1016/j.cjph.2017.05.030
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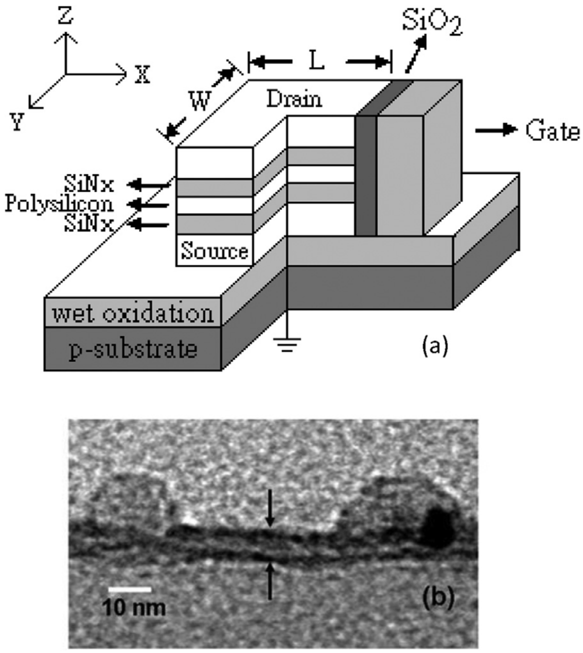

Fig. 1. (a) Schematic diagram of nanopillar transistor structure. A $SiN_x/Si/SiN_x$ quantum dot $10 \times 10 \times 9\,nm^3$ in size is in the center. The Al side gate is ~6 nm away from the dot. (b) TEM picture of the $SiN_x/Si/SiN_x$ layers after deposition. Bobbles on the sides are Ga^+ accumulated through use of a focused ion beam.

The transistor, schematically drawn in Fig. 1(a), was fabricated on p-type (100) silicon wafers. It basically features a central polysilicon layer separated from the top and bottom contacts by two nitride barriers. This dot cavity has a critical length of 3 nm and is closely coupled to a gate electrode at the side. The fabrication of the device proceeds as follows; we first deposited the multilayer structure of SiNx (3-nm)-polysilicon (3-nm)-SiNx (3-nm) sequentially via low-pressure chemical vapor deposition (Fig. 1(b)), and then chemically etched it to create a nominal plateau of $200 \times 140 \times 210\,nm^3$. The source electrode is located at the bottom of the 200 nm thick structure, and has a sheet resistance of $\sim 30\,\Omega\ /cm^2$ achieved via doping with $1x10^{19}\,cm^{-3}$ P^+ in the mixed gas of SiH_4 and PH_3. To prevent electrical short circuits, a short oxidation time using rapid thermal annealing for 30 s was then carried out to seal the nanopillars (creating ~1.5 nm oxide). Next, a contact window (~20 nm wide) was opened on the top nitride layer to form the drain contact. To do this, a layer of tetraethylorthosilicate (TEOS) ~200 nm thick was first grown to level the height of the plateau, and then spun coated with a layer of photoresist.

After development, the exposed TEOS in the upper-right area was cleaned off. Following another chemical etch to further miniaturize the nanopillars, a short oxidation was applied. The photoresist which remained at this stage was used as a hard mask for wet etching in H_2O and HF (ratio 50 to 1) for about 1 min. This lateral etch creates a cut underneath, and opens an active zone. After the strip of the photoresist, polysilicon was defined at a normal angle with respect to the source. The overlap region of both electrodes therefore defines the nanopillars with an outside dimension of $\sim 20 \times 20 \times 9\,nm^3$. To further squeeze the cavity, the technique of self-aligned oxidation was used to add another ~6 nm layer of oxide, giving a total thickness of ~9 nm, and resulting in a quantum dot of $10 \times 10 \times 9\,nm^3$ in size. The last step of the fabrication process consisted of the sputter deposition and etching of Al (300 nm) to provide a side gate next to the cavity.

The device was then loaded into a probe station (PS150, Cascade Microtech, USA) for current-voltage measurements. A HP 4156 C three-terminal meter, with a resolution of 1 mV and 10 fA, was used. Since our model is intimately related to the manner of electrical charging, the pulsed voltages are schematically drawn in Fig. 2(a). Within a time period of 1 mS, 1 mV was applied in the first half cycle. After that, another 1 mV was added (for a total of 2 mV on the device) in the next period.

Such a type of charging is commonly used by experimentalists, as it can avoid overheating. However, it is also the cause of mechanical vibration. In Fig. 2(b), when certain amounts of charge Q_s are accumulated on the surface of the bottom nitride layer, a force it will be created which can bend the layers. At the other end of the layer, a positive current $+I(t)$ is then produced. The elasticity of all the layers, here marked as the energy ΔE, will then force a backward movement to create a negative current $-I(t)$. As a consequence, the current starts to alternate. Correspondingly, the displacement x(t) will change between $+\alpha$ and $-\alpha$, as illustrated in Fig. 2(c).

The theoretical model best suited to describe such behavior is the dynamical equation $m\ddot{x}(t)+c\dot{x}(t)+kx(t)=f(t)$ [17], where $\ddot{x}(t)$ is the second order time derivative of x(t); $\dot{x}(t)$ is the first order derivative; x(t) is the displacement; m represents the mass of the system, as shown in Fig. 3, c denotes the damping coefficient, k is the spring constant, and f(t) is the applied force.