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# POSSIBLE SELF-SELECTION OF TUNNEL CHANNELS WITH REPRODUCIBLE ELECTRICAL PARAMETERS

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Coulomb correlations may cause self-selection of quasi-one dimensional current channels in specially prepared granulated material. Characteristic resistance $R_0$ of single channel is much larger than resistance quantum $R_K$. It depends on bulk properties of material and on macroscopic geometry of the sample, and may be tuned by nearby gate. Total resistance of the sample becomes quantized in units of $R_0$. Values of $R_0$ and control voltages may be *reproducible* from sample to sample. We discuss present experimental status of this idea and its possible applications to single-electron devices operating at up to room temperature.

When typical size (and typical capacitance $C$) of conducting piece scales down, it generates new energy scale $E_C \equiv e^2/C \gg k_B T$ well above thermal noise ($e$ is electron charge). Providing weak interface to outer world here gives decisive role to *macroscopic charge quantization* [1,2]. $E_C$ may range from $k_B \cdot 1$ K (aluminum island between tunnels made with $e$-beam lithography [2] - numerously demonstrated experimental result) to $k_B \cdot 10^3$ K (our hypothetical claim for naturally grown metallic islands, experimentally approved for grains within polysilicon channel [3]).

## 1. Charge quantization with one-junction isolation

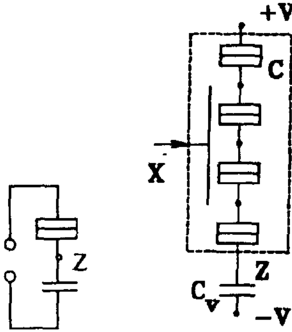
Consider (fig.1) the simplest system which allows for changing the quantized charge $q = en$ of metallic island $Z$. Let full capacitance of the island $Z$ be $C$ (sum of tunnel and non-tunnel capacitances) and tunnel resistance of the junction be $R$. We want energy of the island be sensitive to the number of electrons residing on the island. So we should compare *level spacing* $\Delta E$ (energy difference for the states with $|\Delta q| = e$) with quantum *linewidth* $\delta E$ of the energy level and $k_B T$ scale:

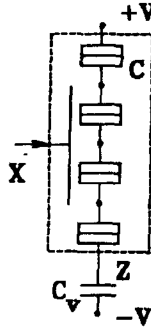
$$\delta E \ll |\Delta E|, \quad k_B T \ll |\Delta E|. \tag{1}$$

Linewidth $\delta E$ is expressed through *lifetime* $\tau_l$ of an exited charge state: $\delta E \simeq \hbar/\tau_l$. Typical voltage across junction $V \simeq -\Delta E/e$. Average tunnel current $\langle I \rangle = e/\tau_l$. By definition of tunnel resistance: $R \simeq V/\langle I \rangle = (-\Delta E/e)/(e/\tau_l)$. Hence $\tau_l \simeq e^2 R/(-\Delta E)$, $\delta E \simeq -\hbar\, \Delta E/e^2 R$. Estimate $\Delta E \simeq -E_C$ gives typical lifetime $\tau_l \simeq RC$, and with eqs. (1) leads to the conditions ($R_K \equiv 2\pi\hbar/e^2$):

$$R \gg R_K/2\pi = 4.1 \ \text{k}\Omega, \quad C \ll e^2/(k_B T). \tag{2}$$

Today $Al/AlO_x/Al$ tunnel junctions fabricated by electron-beam lithography with tunnel barrier thickness $d = 2$ nm and area $A = 50 \times 50$ nm$^2$ have [4] $R \simeq 100$ k$\Omega$. Tunnel resistance $R$ can not be raised further because this would strongly decrease reproducibility of the samples. Island capacitance $C$ here is of the order of tunnel capacitance. Hence $E_C \simeq k_B \cdot 10$ K and with $T \ll 10$ K we expect required charge quantization.





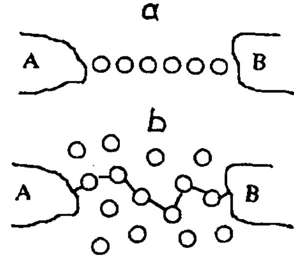



Fig.1 Fig.2 Fig.3

Fig.1. Single-electron box. Divided rectangle denotes tunnel junction with tunnel resistance $R$. Voltage source is on the left

Fig.2. Island $Z$ isolated with chain of $N = 4$ junctions. Both states $n_z = 0$ and $n_z = 1$ minimize energy eq. (3) and are separated with multiple tunnel barrier. Transition $0 \to 1$ can be forced by applying (and then removing) negative signal (voltage or charge) to gate $X$ capacitively coupled to the chain of junctions

Fig.3. $a$ – Ideal chain of nanoscale granules between conducting terminals A and B would be nice but cannot be realized. Gate electrode (not shown) could be placed atop and across the chain or positioned aside. $b$ – In composite media of metallic balls stuffed into insulator electrons select quasi-1D channel of balls

Tunneling electron should dissipate certain energy $E_{diss}$. Otherwise it will not settle on the target island and will form coherent state involving two or more islands. The duration of this dissipation is in fact *a time $\tau$ of tunneling.* Dissipation is needed for the whole macroscopic system to sense tunneling. As $\tau \simeq \hbar/E_{diss}$ and $E_{diss} \simeq |\Delta E|$, eqs. (2) lead to relation $\tau \ll \tau_\ell$: electron stays most of the time ($\tau_\ell$) on a certain island, and only rarely and quickly (spending $\tau$) changes place. For typical lithography parameters [4] we have: $\tau \simeq \hbar/\left(e^2/C\right) = 1 \times 10^{-12}$s, $\tau_\ell \gtrsim RC = 2 \cdot 10^{-10}$s, which illustrates accuracy of eqs. (1) in such systems.

Let $i$ number 'internal' islands with fixed charge $en_i$, $x$ number 'external' islands with fixed voltages $\Phi_x$, and $N_x$ be number of electrons which entered external island since some initial moment. Then full energy of the system comprising electrostatic field of the islands and external voltage sources is [1,5]:

$$E(n, N, \Phi) = (1/2)\, e^2 \sum_{ii'} n_i C^{-1}_{ii'} n_{i'} + e \sum_{ix} n_i D_{ix} \Phi_x + e \sum_x N_x \Phi_x. \qquad (3)$$

This energy (along with thermal contribution) can be spent for dissipation while tunneling. Eq. (3) gives Coulomb spectrum of Fermi levels of the system as a function of its electrostatic state.

## 2. Charge quantization with tunnel-chain isolation

Poor accuracy of charge quantization in single tunnel device above can be improved if we replace single tunnel with chain of $N \geq 2$ tunnel junctions with approximately equal capacitances $C$ (see fig.2). Today lithographic technology can minimize stray capacitance of the islands between junctions: $C_s \ll C$. If employed voltages $V$, $X$ are of the scale of $E_C/e$, system on fig.2 exhibits useful property. Its electrostatic energy given by eq. (3) is never minimized when non-zero number

of electrons occupies islands *between* junctions. Only electron residing on either $Z$ or $+V$ electrodes forms (quasi-) stable state. Electron sitting on $Z$ sees between $Z$ and $+V$ a number of energetically unfavorable positions between junctions and thus it is isolated with multiple tunnel barrier from another nearest stable position on $+V$. This complex barrier may by suppressed (allowing change of $n_z$) either by changing voltage $V$ [6] (which we associate with a DC voltage source), or by applying negative voltage to gate $X$ , or (most important here) by simply removing electron charge $e$ from gate $X$. Beginning with $n_z = 0$, and keeping $V =$ const we can switch to $n_z = 1$ just manipulating gate signal. The approach to process and store one-bit information this way was proposed in [6].

Device (of $N = 7$ $Al/AlO_x/Al$ junctions with $R \sim 300$ k$\Omega$, size ~50×70 nm$^2$, fabricated with $e$-beam lithography ) shown on fig.2 was tested in [7]. Trapping energy barrier height was $k_B \cdot 3.5$ K and typical $V \simeq 1$ mV, $n_Z$ was steady for over two hours at 50 mK.

## 3. Quasi-stable states. Quantum and thermal noise

So tunnel chain provides much better isolation and charge states of the node $Z$ become quasi-stable. In Section 1 we stressed that it is important to avoid coherent mixing of discrete charge states. Let us assess how this contributes to decay of quasi-stable states. Consider device on fig.2 with $N = 2$ in a state $n_z = 1$ in such a bias configuration that $E(n_z = 1) > E(n_z = 0)$. Simple one-electron tunneling is still suppressed as position on the intermediate island between tunnels has energy $E(n_{int} = 1, n_z = 0) > E(n_{int} = 0, n_z = 1)$. Thus a new complex potential barrier involving forbidden state $n_{int} = 1$ is formed (it is evidently no ordinary tunnel barrier of the junctions). But this states $n_z = 1$ and $n_{int} = 1$ can form a coherent mixture of states which will be able to decay adding one electron to $+V$ and thus subtracting it from $Z$. Mixture decays with right energy balance $\Delta E < 0$ and we expect it to have our regular decay probability $1/\tau_t$. But probability for this non-stationary mixture to find itself near the energy $E(n_{int} = 1, n_z = 0)$ is $\delta E/\Delta E$ [8]. So for escape time $\tau_Q$ of the trapped electron due to quantum coherency mixing we have: $1/\tau_Q \simeq (\delta E/\Delta E)\,(1/\tau_t)$. Recalling Section 1 we get: $\tau_Q \simeq (2\pi R/R_K)\,\tau_t$. When $N > 2$ coherent mixture should embrace approximately $N - 1$ forbidden states before it will be able to decay regularly. By induction we get $\tau_Q(N) \simeq (2\pi R/R_K)^{N-1}\,\tau_t$.

For realization [7] of aluminum trap this gives $\tau_Q(7) \simeq 10^{13}$ s, which is still very little on the error scale of modern computers [5]. So increasing $N$ and $E_C$ parameters, we have more pronounced macroscopic charge quantization.

Another reason to increase $N$ and $E_C$ is classic expression for thermally activated escape time $\tau_T \simeq \tau_t \exp(E_{tr}/k_B T)$. For $N$-trap trapping barrier height is [7] $E_{tr} \simeq E_C N^2 C_v/(C + NC_v)$. So $\tau_T$ grows with $N$ and $E_C/T$. Even at exotic $T = 50$ mK the system [7] has $\tau_T \simeq 10^{18}$ s.

## 4. Self-organization of 1D ball current chains in naturally grown composite media

Above we have seen that only multi-junction isolation of metallic island can lead to practical single-electron devices. Analysis [9] shows that increasing $N$ and $E_C$ do bring the desired accuracy (with each junction defined lithographically) only provided uniformity of the tunnels is high and there are no charged contaminations in the vicinity of reference nodes and junction chains. Aluminum technology

employed in [6] is seemingly near best possible $E_C$ and uniformity values, provided *e*-beam lithography is used to make *each* tunnel in a chain. The same applies to the approach [2] with gated Schottky barriers separating 100 nm lakes of 2D electron gas (2DEG) in GaAs/AlGaAs heterostructures. Both approaches leave us within 10 mK operating temperature range. Modern tendency is to leave *e*-beam patterning only for wiring leads and for outlining general shape of chains. Junctions and islands within this outlined chains are provided by more 'natural' means before or after *e*-beam stage.

This seems to be is a way to essentially increase operating temperature without loss of charge quantization accuracy. Consider lonely metallic ball with radius $r = 2$ nm incorporated into media like $SiO_2$ with typical dielectric constant $\varepsilon = 5$. For this our Coulomb scale becomes $E_C = e^2/(2 \cdot 4\pi\varepsilon\varepsilon_0 r) = k_B \times 10^3$ K. Of course, any tunnel barrier touching this ball will increase its capacitance and decrease $E_C$, but later we will see how this effect can be made small.

There was an old idea [2] to grow chains of such granules between some conductors (fig.3*a*) due to some self-assembly of such chains. The only obstacle being the lack of realization of such a self-assembly process.

But today we have well established technology [10] which provides us with precisely controllable media of conducting balls staffed into insulator. With this we can transform old idea of self-assembly *at the stage of system construction* into the idea of self-organization of 1D ball current channel *at the stage of current transport* through the disordered composite media. Electrical properties of this channel will be reproducible and depend only on material parameters of the media and on its overall geometry. To achieve this feature, technology should carefully control mean radius $r$ of the balls, form and width $\Delta r$ of the distribution of the radius, mean minimal separation $l$ between immediate neighbors, thickness $T$, length $L$ and width $W$ of this composite film containing balls.

Consider fig.3*b*. Let $\Delta r \simeq r/2$. As $l$ is dispersed too, energy $E_C$ needed to charge a ball with one extra electron will be essentially varied from ball to ball. Probability to populate ball is $\sim\exp(-E_C)$ which is a sensitive function of $E_C$. At low temperature and with small voltage applied between $A$ and $B$, we evidently have Coulomb blockade of electron transport. As voltage increases towards the threshold of Coulomb blockade, we expect that the threshold will be lifted first due to formation of a single shortest chain of balls with lowest $E_C$ and separated with smallest $l$.

Mean $l$ must be chosen so that it leads to typical tunnel resistance between balls $R \simeq 100$ kΩ. In Section 1 we saw that this is enough for good localization of the electron on a distinct ball. Looking at reference parameters given in Section 1, we might say that to get $R(r,l) \simeq 100$ kΩ with $r \simeq 2$ nm we should have $l \simeq 1$ nm. To estimate volume concentration of metal in our composite material let us assume for a moment that balls form cubic lattice. This lead to value $\rho_V \simeq (4\pi/3)\, r^3/(2r + l)^3 \simeq 0.2$ which can be easily provided by technology [10]. But sure residual contaminations in the media between balls will form localized centers which will facilitate electronic transport [11] and reduce effective $R$. To improve $R$ reduction we need increase $l$ say an order of magnitude, that is up to $l \simeq 10$ nm. Corresponding metal volume concentration $\rho_V \simeq 0.02$ which is even easier to get. At the same time this value of $l$ justifies our assumption made above that full capacitance of the ball in such a media can be only few percent more than the capacitance of the lonely ball.

If channel goes too far from straight line its total resistance will go too high and less resistive (and more straight) channel will emerge. So we can estimate number of balls in our channel as $N \simeq L/l$. Then its total resistance is $R_0 \simeq RL/l$. Recall that now we have $r \simeq l$ which means that self-capacitance of the ball is no less than 'tunnel' capacitance. This makes irrelevant estimates for trapping barrier height made in Section 4. Here complex barrier height will be of the order of $E_{tr} \gtrsim E_{Cmin}$, where $E_{Cmin} \simeq e^2/(2 \cdot 4\pi\varepsilon\varepsilon_0(r + \Delta r))$ is typical charging energy of the most energetically favorable balls.

It seems reasonable to choose width and thickness of the film so that $W \simeq 3l$ and $T \simeq 3l$ to ensure that electrons have enough choice to select proper 1D ball chain. But this choice should be not too rich to ensure that formation of no more than exactly one channel be most probable near the threshold.

Total Coulomb threshold for transport voltage is $V_{th} \simeq E_{tr}/e$. As transport voltage grows beyond typical value of $V_{smea} \simeq E_{Cmax}/e$ with $E_{Cmax} \simeq e^2/(2 \cdot 4\pi\varepsilon\varepsilon_0(r - \Delta r))$, the single-channel picture will be evidently smeared out with multiple-channel net current flowing atop of all the barriers. The latter regime was carefully analyzed long ago [12]. For voltages $V$ such that $V_{th} < V < V_{smea}$ we expect gradual transition from one-channel current to net current. For more narrow but finite range of voltages $V$ above $V_{th}$ and for finite range of gate voltages we can expect that the same single channel persists with his resistance dependent on gate voltage. Note that for $\Delta r \simeq r/2$ we have $V_{smea} \simeq 3V_{th}$.

Estimates above give only mean statistical value of electrodynamic parameters characterizing our 1D ball channel. We can estimate fundamental deviations from these values noting that number $N$ of balls in the channel inevitably fluctuate at least as $\Delta N = 1$ from sample to sample. We see that total resistance of the channel has error $\simeq \Delta N/N$ and can be kept within 10% with the choice $N = 10$. But threshold $V_{th}$ and typical gate voltages needed to modulate current do *not* depend on $\Delta N$.

Two mechanisms contributes to the formation of 1D ball channel with proper tunnel resistance between balls.

- Electrons prefer balls with lowest charging energy $E_C$.
- If two balls are too close together so that resistance $R \simeq R_K$, then electrons do not distinguish these balls. Such a pair should be regarded as a composite ball within a channel. We see that even if technology accidentally places some of the balls too close to each other, proper values $R \gg R_K$ will be found anyway.

## 5. Quasi-1D ball current channel versus quasi-1D ballistic current channel

Note that the whole picture is based on energy balance consideration and should *not* be sensitive to the nature of electron transport between balls. This transport may be a mixture [11] of direct tunneling between balls, resonant tunneling via localized centers, thermally activated jumps etc. We just need maintain conditions (such as parameters $r$, $l$) ensuring absence of coherent mixing of electrons residing on different balls. Our parameter $R$ may have more general meaning of typical value of differential resistance at low voltages for voltage-biased pair of balls. That is why we try to escape name 'tunnel channel' in favor of 'ball current channel'.

Our self-selected 1D ball channel has resistance much more that resistance quantum $R_0 \gg N \cdot R_K$ and it can be modulated by external gate because of

modulating trapping barrier height. Channel itself (as a geometrical entity) stays intact within finite gate voltage range.

Recall that quasi-1D ballistic current channel in mesoscopic samples each have resistance $R_K$ and external gate can only change the number of such channels that can fit into the sample. This leads to quantization of longitudinal resistance. Recall that electron wave function preserves coherency along the whole length of the ballistic channel and electrochemical potential has the same value along it.

In our ball current channel wave function coherency is intentionally broken at each inter-ball spacing. After each tunneling or hopping event electron thermalizes on the new ball and sits down to the new Fermi level characteristic to the given charge state of the system.

## 6. Experimental status of the 1D ball channel idea

Up till now idea of self-selection of quasi-1D ball channel was demonstrated only in non-metallic domain. But studies in different media justify the opinion that it is not the details of the structure, but geometry and capacitance that govern this phenomenon [11].

Authors of [13] used a GaAs wafer randomly $\delta$-doped with Si donors ($5{\cdot}10^{12}$ $cm^{-2}$) within a few atomic layers. This thin Si-doped layer is about 10 nm below 2DEG layer which in turn is about 20 nm below GaAs surface. To outline chain shape a strip was left (by regular $e$-beam lithography means) in 2D electron gas which was 150 nm wide and 200 nm long. Adjusting voltage applied to the side gate, it is possible to force formation of lakes in 2DEG which are $\simeq$ 10 nm in size and are exactly atop of each donor. Lakes are isolated with barriers of typical tunnel resistance $R \simeq 100$ kΩ. Self-selection of lakes with reference to lowest charging energy $E_C$ organized a valley: one-dimensional chain of up to 10 lakes through which tunnel current can flow.

Fabricated devices similar to fig.2 (regarded as memory cells) demonstrated escape time of several hours at much higher $T = 4.2$ K. Unfortunately this approach is (evidently) heavily bounded with unpredictable background charges of the lakes. To combat this, authors of [13] employed $n$-electrons-per-bit coding with $n$ up to 40.

To outline tunnel chain authors of [3] deposited 4-nm-thick, 100-nm-long, 100-nm-wide strip of amorphous Si. During subsequent crystallization, vertical cylinder crystals were formed 4 nm high, 10 nm in diameter. Similar to Section 4, valley of 1D chain of up to 15 grains was formed. Isolated from the valley with multiple barrier there always exists another grain with low $E_C$ which represent the most deep 'swamp'. Discrete electrons enter or leave the swamp following appropriate gate signal. But the tunnel current flowing through the valley is greatly influenced by the charge state $n_{sw}$ of the swamp. $|\Delta n_{sw}| = 1$ can change the current from 60 pA to <0.1 pA with transport voltage of 20 mV even at room temperature. Both such states survived for no less than one hour at $T = 300$ K. Switching to any of $0 \leq n_{sw} \leq 5$ states following gate signal was demonstrated. Authors called their device 'read-only memory for mobile computers/communicators'.

Paper [3] has been heavily criticized for too straightforward interpretation of mechanism involved. Basic issue of what is the physical reason of electron localization on poly-silicon grains seems very far from understanding. Still this paper seems very important because it demonstrates: 1) self-selective nature of ball chains and 2) definite ability to control channel resistance with external gate.

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