Preprint Title High dynamic resistance elements based on Josephson junction array

Authors Konstantin Arutyunov and Janne S. Lehtinen

Publication Date 11 Nov 2019

Article Type Full Research Paper

ORCID® iDs Konstantin Arutyunov - https://orcid.org/0000-0001-9373-5185; Janne S. Lehtinen - https://orcid.org/0000-0002-5334-016X

High dynamic resistance elements based on Josephson junction array

Konstantin Yu. Arutyunov*[1, 2] and Janne S. Lehtinen[3,4]

Address:

[1]National Research University Higher School of Economics, 101000, Moscow, Russia

[2] P.L. Kapitza Institute for Physical Problems RAS, Moscow, 119334, Russia

[3]*VTT Technical Research Centre of Finland Ltd., 02150 Espoo, Finland.*

[4] *Department of Physics, University of Jyvaskyla, PB 35, FI-40014 Jyvaskyla, Finland.*

Email: karutyunov@hse.ru

* Corresponding author

Abstract

Chain of superconductor-insulator-superconductor junctions based on *Al-AlO*$_x$*-Al...* lift-off fabricated nanostructures was measured at ultra-low temperatures. At zero magnetic field the low current bias dynamic resistance can reach values ~10^{11} Ω. The system has been proved to provide a decent quality current biasing circuit enabling observation of Coulomb blockade and Bloch oscillations in ultra-narrow *Ti* nanowires associated with quantum phase slip effect.

Keywords

nanoelectronics; superconductivity; Josephson junction array; dynamic resistance

Introduction

Modern nanolectronics faces stignation of further miniaturization deviating from the Moor's law [1]. Typically two main reason are quoated: severe heat dissipation per unit volume (surface), and various quantum phenomena driving the operation of ultra-small devices from conventional (classical) regime. The radical solution of the first problem is to build critical elements using superconductors. The basics of the approach have been formed in late 80th resulting in RSFQ (rapid single flux quantum) logic [2]. Since that time the concept has never been completely abandoned. However the corresponding systems so far have not developed into mass market commercial products, being limited solely to particular ‘cost-no-object’ applications. Nowadays the situation with superconducting electronics starts to develop much faster mainly due to understanding, that even taking into consideration the necessity of refrigeration, the energy consumption of the next generation supercomputers can be limited to ~ 10 MW, compared to ~100 MW if to use conventional semiconductor CMOS (complementary metal–oxide–semiconductor) technology. In parallel with heat dissipation, another issue is the speed of processing. It has been shown that the operational frequency of superconducting logic can be at least 100 times higher then with CMOS-based devices. It is universally accepted that the limiting factor for the speed of operation of various superconducting devices is the high-frequency impedance, e.g. originating from kinetic inductance. The effect should be taken into consideration for various cryoelectronic applications.

In addition to RSFQ computers expoiting classic 2-bit logic, during the last decades there has been observed an increasing interest towards *quantum computing*, utilizing non-classic approach. There has been multiple suggestions how to build quantum logic elements, *quantum bits* (*qbits*), including superconducting systems based on Josephson effect. It has been shown that physics of a Josephson junction (JJ) is dual to a quantum phase slip junction (QPSJ) [3], and the corresponding QPSJ-based qbit operation has been demonstrated [4]. At the same moment, quantum dynamics of a JJ (or a QPSJ) is strongly determined by the environment [5,6]. In particular, utilization of devices based on quantum fluctuations of macroscopic phase φ mandatory requires stabilization of the quantum conjugated quantity - charge q. The most straightforward approach is to use high-Ohmic on-chip current-biasing elements [7, 8, 9,10]. However, later it has been noticed that resistive dissipative elements inevitably act as sources of Johnson noise, leading to degradation of system performance [11].

Here we present experimental study of quasi-1D chain of JJs. The approach has demonstrated to provide decent high-frequency impedance to study QPS phenomena without noticeable undesired impact of Johnson noise associated with dissipative elements [12].

Experimental

Conventional lift-off e-beam lithography followed by ultra-high vacuum deposition of materials was used for fabrication of the nanostructures. Hybrid QPSJ samples were made of *Ti, Al* and aluminum oxide [12]. Test high-impedance JJs, studied in this paper, being similar to the ones from [12], were fabricated from superconducting thin film *Al* oxidized *in situ* to form tunnel barriers. The samples were analyzed by scanning electron (SEM) and atomic force (AFM) microscopes (Fig. 1).

Transport measurements were made inside ^{3}He^{4}He dilution refrigerator at temperatures below 400 mK, corresponding to superconducting transition of *Ti*

QPSJs [10, 12]. All input / output lines were carefully filtered [13] to reduce the impact of noisy electromagnetic environment. When necessary, small magnetic field up to 0,05 T was applied using small superconducting coils wounded directly on sample holder cap.

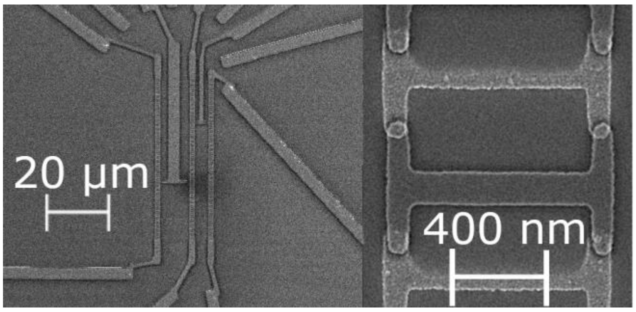

Figure 1: SEM images of the test sample fabricated from superconducting thin film aluminium oxidized *in situ* to form tunnel barriers. Left panel: overview of the structure. Right panel: zoom of the JJ element.

Results and Discussion

The ultimate goal of the project is to study quantum dynamics of QPSJ, system dual to JJ [3], including observation of Coulomb blockade and Bloch oscillations [14]. Given that macroscopic phase φ and charge q are quantum conjugated values $[\hat{\varphi},\hat{q}]=ih$, to enable the high rate of phase fluctuations one should define the charge. Hence, to enable this regime, electric current I through the QPSJ, being just the time derivative of charge $I=dq/dt$, should be stabilized. Note that here the finite electric current is maintained by correlated Cooper pair tunnelling at a voltage bias V across the QPSJ exceeding the particular Coulomb blockade threshold V_C [14]. The tunnelling happens at *Bloch oscillation* rate f_B. Syncronization of this 'internal' periodic process with external drive f_{RF} should result in quantized singularities (*Bloch steps*) at current values $I(n)=n(2e)f_{RF}$, where $2e$ is the charge of

Cooper pair and n = 1,2,3... are integers. Resuming, study of QPSJ *I-V* characteristics demonstrating Coulomb blockade at zero current *I*=0 and voltages $V<V_C$ requires just the high-Ohmic environment with resistance R_{env} exceeding the quantum value $R_{env}>R_Q=h/e^2\approx 26$ kΩ. While at finite currents *I*>0 one needs current stabilization at high frequency f_{RF}, extending the requirement to high value of the high-frequency impedance $Z_{env}(f_{RF})$. Observation of pronounced Coulomb blockade has been observed in JJs using both high-resistive dissipative environment [7,8] and non-linear Josephson elements with high dynamic resistance and/or kinetic inductance [6,15]. However, an extended attempts to observe Bloch oscillation phenomena at finite currents in JJs provided rather modest results [7,8,16]. Recent progress in understanding of QPS phenomena [17] in ultra-narrow superconducting channels has revived the interest resulting in observation of decent Coulomb blockade [9,10], while quite blurred Bloch steps at finite currents have been detected so far [10]. Later it has been understood that the straightforward approach of using high-Ohmic dissipative environment $R_{env}>R_Q$ is far from being optimal introducing Johnson noise washing out the desired current singularities [11]. Various JJ-based systems were suggested taking advantage of high kinetic inductance of a SQUID [18, 19] $L_k = \cos^{-1}\left(\frac{\Phi}{\Phi_0}\right)$ at a degeneracy point when $\Phi/\Phi_0\rightarrow\pi/2$, where Φ is the magnetic flux through the SQUID area and Φ_0 is the flux quantum $\Phi_0 = h/2e = 2\times10^{-15}$ Wb. Hence the SQUID-based approach requires application of finite magnetic field. Given that the electromagnetic horizon of our QPSJ is of the order of ~100 μm, [20,21,22], the corresponding high-impedance current biasing circuit should be of appropriate (small) dimensions. Thus the area of SQUIDs is small, and hence the magnetic field corresponding to $\Phi/\Phi_0= \pi/2$ can easily reach ~ 10 mT range. At such magnetic field two undesired effects might happen both with the biasing superconducting leads and with the QPSJ under interest: formation of Abrikosov vortices and noticeable suppression of the energy gap. Consequently, in our approach we opted for a non-dissipative (superconducting) high-impedance environment in zero magnetic field.

Our quasi-one-dimensional arrays of superconductor-insulator-superconductor (SIS) junctions did contain loops forming SQUIDs (Fig. 1). However, probably due to charging effects, the Josephson current was very small (Fig. 2a), and application of magnetic field just monotonically suppressed the superconducting gap. The corresponding *I-V* dependency can be understood like a tunnel characteristics of multiple SIS junctions connected in series. At zero magnetic field the dynamic resistance $R_{dyn} \equiv dV/dI$ of such SIS element can reach ~10^{11} Ω at small current bias (Fig. 2b).

The corresponding SIS junction chain has been used to current bias narrow *Ti* nanowires [12], with cross sections demonstrating various phenomena attributed to QPS effect [23, 24,10, 25, 26, 27, 28, 29, 30]. The observation of Coulomb blockade and Bloch steps [12] confirms the usefulness of the suggested concept: utilization of SIS junction chains.

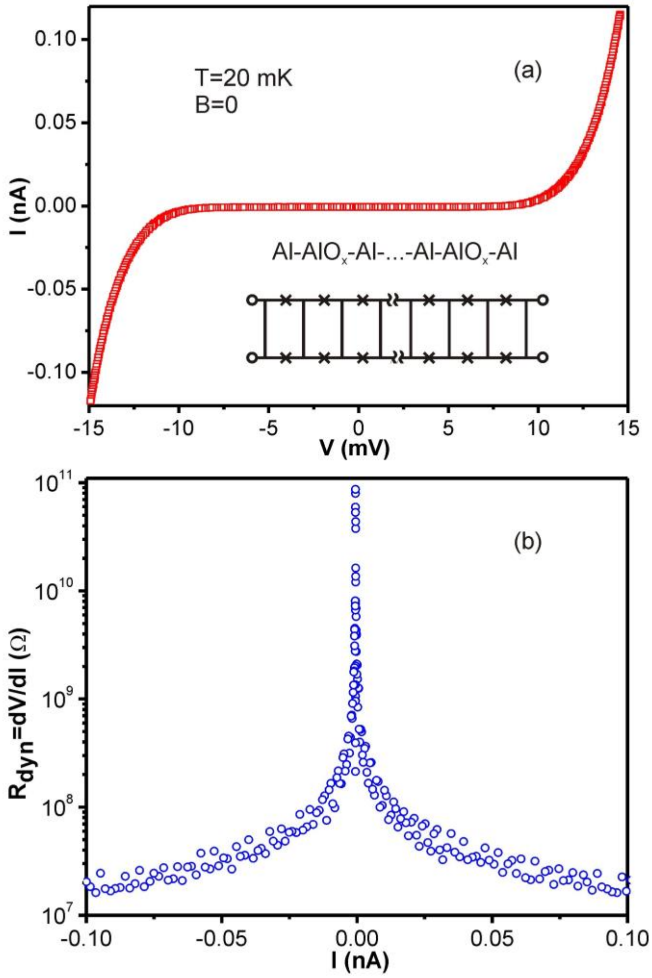

Figure 2: (a) Experimental I-V characteristics of 50 pairs of Al-AlO_x junctions connected in series. Inset shows the schematics of the structure. (b) Dynamic resistance $R_{dyn} \equiv dV/dI$ obtained by numeric differentiation of the I-V dependence.

Acknowledgements

The article was prepared within the framework of the Academic Fund Program at the National Research University Higher School of Economics (HSE) in 2019 — 2020 (grant №19-01-050) and by the Russian Academic Excellence Project «5-100».

References

[1] Moore, G. *Electronics,* **1965**, *38(8)*, 1 – 4.

[2] Likharev, K. K. and Semenov, V.K. *IEEE Transactions on Applied Superconductivity* , **1991**, *1* , 3 – 28.

[3] Mooij J., and Nazarov, Y.V. *Nat. Phys*. **2006**, *2*, 169 –172.

[4] Astafiev, O. V. , Ioffe, L. B., Kafanov, S. , Pashkin, Yu. A. , Arutyunov, K. Yu. , Shahar, D., Cohen, O. and Tsai, J. S. *Nature* **2012,** *484(7394),* 355 – 358.

[5] Schön, G. and Zaikin, A. D. *Phys. Rep*. **1990**, *198*, 237 - 412.

[6] Watanabe, M. and Haviland, D. B. *Phys. Rev. Lett*. **2001**, 86 , 5120 – 5123.

[7] Kuzmin L. S. and Haviland D. S. *Phys. Rev. Lett*. **1991**, *67*, 2890 **–** 2893.

[8] Kuzmin, L.S. and Haviland, D. B. *Physica Scripta* **1992**, *T42*, 171-176.

[9] Hongisto, T. T. and Zorin, A. B. *Phys. Rev. Lett*. **2012,** *108***,** 097001-1– 097001-5

[10] Lehtinen J. S., Zakharov, K., and Arutyunov, K. Yu. *Phys. Rev. Lett*. **2012,** *109***,** 187001-1 – 187001-5.

[11] Webster, C. H. , Fenton, J. C. , Hongisto, T. T. , Giblin, S. P. , Zorin, A. B. and Warburton P. A. *Phys. Rev. B* **2013,** *87*, 144510-1 – 144510-12.

[12] Wang, Z. M., Lehtinen, J. S. and Arutyunov, K. Yu. *Appl. Phys. Lett*. **2019**, *114,* 242601-1 – 242601-6.

[13] Zavyalov, V. V., Chernyaev, S. A. , Shein, K. V. , Shukaleva, A. G. and Arutyunov, K. Yu. *Journal of Physics: Conference series* **2018**, *969*, 012086 1 – 012086-6.

[14] Averin, D. V. , Zorin, A. B. and Likharev, K. K. *Sov. Phys. JETP* **1985**, *61(2)*, 407-412.

[15] Watanabe, M. and Haviland, D. B. *Phys. Rev. B* **2003***, 67,* 094505-1 – 094505-11.

[16] K. Andersson, “Coulomb blockade of Cooper pair tunneling in one dimensional

Josephson junction arrays," Ph.D. thesis (Department of Physics, Royal Institute of Technology, Stockholm, 2002).

[17] Arutyunov, K. Yu., Golubev, D. and Zaikin, A. D. *Phys. Rep*. **2008**, *464*, 1 – 70.

[18] Bell, M. T., Sadovskyy, I. A., Ioffe, L. B., Kitaev, A. Yu. and Gershenson, M. E. *Phys. Rev. Lett*. **2012**, *109*, 137003-1 – 137003-5.

[19] Masluk, N. A., Pop, I. M., Kamal, A., Minev, Z. K. and Devoret M. H. *Phys. Rev. Lett*. **2012**, *109*, 137002-1 –137002-5.

[20] Ingold, G. L. and Nazarov, Y. V. "Charge tunneling rates in ultrasmall junctions," in Single Charge Tunneling, NATO ASI Series (Series B: Physics), edited by H. Grabert, M. H. Devoret (Springer, Boston, MA, 1992), Vol. 294.

[21] Wahlgren, P., Delsing, P. and Haviland, D. B. *Phys. Rev. B* **1995,** *52*, R2293 – R2296.

[22] Wahlgren, P., Delsing, P., Claeson, T. and Haviland, D. B. *Phys. Rev. B* **1998**, *57*, 2375 – 2381.

[23] Lehtinen, J. S. , Sajavaara, T., Arutyunov, K. Yu. , Presnjakov, M. Yu. and Vasiliev, A. *Phys. Rev. B.* **2012**, *85*, 094508-1 – 094508-7.

[24] Arutyunov, K. Yu., Hongisto, T. T., Lehtinen, J. S., Leino, L. I. and Vasiliev, A. L. *NPG: Sci. Rep*. **2013**, *2*, 293-1 – 293-7.

[25] Lehtinen, J. S. and Arutyunov, K. Yu. *Supercond. Sci. and Technology*, **2012**, *25* 124007-1 –124007-5.

[26] Arutyunov, K. Yu., Lehtinen, J. S. and Rantala, T. *J. Supercond. Nov. Magn*. **2016**, *29*, 569 – 572.

[27] Arutyunov K. Yu. and Lehtinen, J.S. *Nanoscale Research Letters* **2016**, *11*, 364-1 – 364-4.

[28] Arutyunov, K. Yu. and Lehtinen, J.S. *Physica C: Superconductivity and its applications*, **2017**, *533*, 158–160.

[29] Arutyunov, K.Yu., Lehtinen, J.S., Radkevich, A.A., Semenov, A.G., Zaikin A.D. *Journal of Magnetism and Magnetic Materials*, **2018**, *459*, 356-358.

[30] Elo, T., Lähteenmäki, P., Golubev, D., Savin, A., Arutyunov, K. Yu. and Hakonen, P. J. *Journal of Low Temperature Physics,* **2017,** *189*, 204-216.