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14. ABSTRACT During these three years project we have made a very significant progress in our research program, especially in the theoretical understanding of the microscopic origin of the noise. Briefly, we came up with microscopic models for charge noise, critical current fluctuations and quasiparticle poisoning which include a completely novel physical origin of these noises. We also proposed a model for excess low frequency flux noise which agrees very well with all existing data. We established strong and very active collaborations with leading experimental groups [NEC,					
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Report Title

Controlling decoherence in superconducting qubits: phenomenological model and microscopic origin of $1/f$ noise

ABSTRACT

During these three years project we have made a very significant progress in our research program, especially in the theoretical understanding of the microscopic origin of the noise. Briefly, we came up with microscopic models for charge noise, critical current fluctuations and quasiparticle poisoning which include a completely novel physical origin of these noises. We also proposed a model for excess low frequency flux noise which agrees very well with all existing data. We established strong and very active collaborations with leading experimental groups [NEC, Tsukuba (Dr. O. Astafiev and Dr. Y. Pashkin), USCB (Prof. J. Martinis), UW-Madison (Dr. R. McDermott), Insitute Ne?el GRENOBLE (Dr. O. Buisson and W. Guichard), Rutgers University (Prof. M. Gershenson] and discussed with them specific experiments to identify the sources of noise. The noise measurements planned by these groups will provide the information that will pinpoint the origin of all these different noise types in the next few years. We believe we are now at the crucial point in our noise origin and full characterization study.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

- 1) L. Faoro and F. W. Hekking, Cross correlations between charge noise and critical current fluctuations in a Josephson coupled circuit, Phys. Rev. B 81, 052505 (2010).
- 2) F. Hoehne, Yu. A. Pashkin, O. Astafiev, L. Faoro, L. B. Ioffe, Y. Nakamura and J. S. Tsai, Dephas- ing in high-frequency metallic nanomechanical resonators, Phys. Rev. B 81, 184112 (2010).
- 3) L. Faoro, A. Kitaev and L. B. Ioffe, Quasiparticle poisoning and Josephson current fluctuations induced by Kondo impurities, Phys. Rev. Lett. 101, 247002 (2008).
- 4) L. Faoro and L. B. Ioffe, Microscopic origin of low frequency flux noise in Josephson circuits, Phys. Rev. Lett 100, 227005 (2008).
- 5) L. Faoro and L. B. Ioffe, Microscopic origin of critical current fluctuations in large, small and ultra- small area Josephson junctions, Phys. Rev. B 75, 132505 (2007).
- 6) J. Bergli and L. Faoro, Exact solutions for the dynamical decoupling of a qubit with telegraph noise, Phys. Rev. B 75, 054515 (2007).
- 7) L. Faoro and F. Taddei, Entanglement detection for electrons via witness operators, Phys. Rev. B. 75 165327 (2007).
- 8) L. Faoro and L. B. Ioffe, Quantum Two Level Systems and Kondo-like Traps as Possible Source of Decoherence in Superconducting Qubits, Phys. Rev. Lett. 96, 47001 (2006).
- 9) L. B. Ioffe and M. Mezard, "Asymmetric quantum error correcting codes", Phys. Rev. A 75, 032345 (2007).
- 10) B. Doucot and L. B. Ioffe, "Voltage-Current curves for small Josephson junction arrays", Phys. Rev. B 76, 214507 (2007).
- 11) M. V. Feigelman, L. B. Ioffe, V. E. Kravtsov and E. A. Yuzbashyan, "Eigenfunction fractality and pseudogap state near superconductor-insulator transition", Phys. Rev. Lett. 98, 027001 (2007).
- 12) S. Gladchenko, D. Olaya, E. Dupon-Ferrier, M. Gershenson, B. Doucot and L. Ioffe, "Evidence for topologically protected states in superconducting nano-circuits", Nature Phys. 5 48-53 (2009).
- 13) L. B. Ioffe and M. Mezard, "Disorder-driven quantum phase transitions in superconductors and magnets", Phys. Rev. Lett 105, 037001 (2010).

Number of Papers published in peer-reviewed journals: 13.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):0

(d) Manuscripts

Number of Manuscripts:0.00

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Lara Faoro	1.00
Lev Ioffe	0.50
FTE Equivalent:	1.50
Total Number:	2

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PhDs

NAME

Total Number:

Names of other research staff

NAME

PERCENT SUPPORTED

FTE Equivalent:

Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

The goal of this 3 years project was to offer theoretical support to experimentalists and material scientists that plan to perform the experiments in order to identify the microscopic sources of noise, to discriminate between different theoretical noise models and to search for low noise materials.

We believe we have made a very significant progress in the theoretical understanding of the microscopic origin of the noise in superconducting circuits. Our major accomplishments have been:

- we have identified a novel microscopic origin of the charge and critical current noise: Kondo- like traps (KT) formed by localized spins at the Superconductor Insulator (SI) interfaces that compete with more conventional charged TLS and might dominate the Gaussian part of the observed noise in superconducting structures. While the TLS noise exists also in the normal state, the KT noise is specific to the superconductors.

At present it is unclear which mechanism is the dominant source of charge noise in different superconducting devices and materials. Though the strongly coupled TLS were directly observed in the spectroscopy of the phase qubits with large Josephson junctions and more recently of Cooper pair box, their density was insufficiently high to explain the low frequency noise in the small-junction qubits, especially its Gaussian component. We showed that the latter one can be well explained by KT mechanism.

Concerning critical current noise, our estimates of the critical current fluctuations produced by TLS in the insulating barrier show that the observed noise agrees well both in magnitude and in temperature dependence with the resistance fluctuations in the normal state measured recently in the Josephson junctions of flux qubits but it is not sufficient to explain the larger critical current noise observed in large superconducting contacts, showing $1/f$ low frequency (up to 100 Hz) noise with intensity increasing proportional to the junction area and T^2 dependence. Both observations can be explained by the KT mechanism. However, a complete phenomenological characterization of critical current fluctuations is still missing. In particular, it would be very important to have direct measurements of the noise in the resistance in the normal state and the critical current noise in the superconducting state. The hallmark of the KT mechanism is the appearance of the additional, almost Gaussian, contribution to the low frequency noise in the superconducting state.

- we showed that the KT mechanism might be responsible for a very slow relaxation of quasiparticles that is the root of the "quasiparticle poisoning" because it leads to the formation of the strongly-localized states of quasi particles at the SI interface. In particular, it seems very likely that the puzzling effect of the normal traps attached to the leads on the quasiparticle dynamics observed in a number of recent experiments is due to KT mechanism of the subgap level formation. However, a more direct experimental test is needed to establish it firmly. It is also likely that this novel mechanism explains the recent data on the slow quasiparticle relaxation in high-Q superconducting resonators.

- we proposed a theoretical picture for the excess low frequency flux noise consistent with data in which the noise is due to the spins at the SI interface coupled via RKKY interaction. In contrast to the alternative models this mechanism explains many puzzling features of the flux noise: its apparent temperature independence down to 20mK, its persistence to at least 20 MHz and the rough SQUID loop area independence. This mechanism generates roughly $1/f$ noise in a broad frequency range but the details of its spectrum at very high and very low frequencies need to be computed for a better comparison with the data. Qualitatively, we expect that the samples with high concentration of such impurities exhibit spin glass ordering (as was recently observed in Mc. Dermott group) and lower noise at very low temperatures. Moreover, our theoretical hypothesis that localized magnetic impurities in the vicinity of the qubit wiring are a key source of low frequency flux noise have been very recently supported by experimental results by Lanting et al. which show that qubits fabricated above a superconducting ground plane yielded lower noise than qubits without such a layer.

- we have identified the noise properties relevant for quantum error correction and information protection. In fact, an important conclusion of our theoretical studies is that all the major sources of noise of present superconducting circuits are local while their effect on the qubits decreases as a large power law of the distance. This is very important in order to decide strategy to encode and process quantum information in superconducting devices. In particular, it supports the view that one does not need to implement recent fault tolerant schemes that require an unrealistic huge redundancy or very large topologically protected arrays that encode information in the noiseless subspace. Instead it might be sufficient to design moderate size Josephson structures that suppress only local noises efficiently.

Technology Transfer