SAND2024-14220J

Quantum Sensing using a Qubit for the Detection of Ionizing Radiation

Matthew L. Freeman[a], Sueli Skinner-Ramos[a], Rupert M. Lewis[a], and Stephen M. Carr[a]

[a]Sandia National Laboratories, Albuquerque NM 87123, USA

ABSTRACT

Quantum sensing utilizes the inherent sensitivity of a quantum system to external stimuli. Our goal is to leverage this sensitivity to develop a quantum sensor designed for the detection of ionizing radiation. Here we report on the design, fabrication, and measurement of a new quantum device for hard x-ray and gamma-ray detection. Our quantum device is based on a superconducting quantum bit (qubit) with superconducting tunnel junctions as the core device elements. We describe our experimental investigation directed toward the detection metrics of energy resolution, dynamic range, and active area. In contrast to existing superconducting detectors, the active area per qubit may be much larger than the physical area of the tunnel junctions or the physical area of the qubit device, due to the sensitivity of quantum coherence to ionizing radiation deposition within a radius on the millimeter or centimeter scale. Our experimental design enables an ionizing radiation source at room temperature to be detected by our quantum sensor at low temperature.

Keywords: qubit, sensing, radiation

1. INTRODUCTION

Qubits are quantum devices that encode information, but unlike classical bits where the information is in a binary state a qubit encodes information in a superposition of states. The most common representation is superposition of the ground and first excited states, $\alpha |0\rangle + \beta |1\rangle$. To limit the qubit to two states, anharmonic ciruits are used and cooled to cryogenic temperatures in a dilution refrigerator. Qubits employed in quantum information processing exploit their non-binary state to solve problems in a larger phase space. The most notable example problem is Shor's algorithm, an algorithm for factoring a large integer into its prime constituents. Due to the number of qubits needed to make a quantum processor, currently no practical problems have been solved by a quantum computer.

While there has been substantial research into developing qubits for computation, there has been comparatively less for quantum sensing. Whereas quantum computing seeks to solve mathematical problems, quantum sensing is using the innate sensitivity of quantum devices to detect external stimuli. An advantage of superconducting quantum sensors is, with exception of frequencies close to the superconducting gap, we have no reason to suspect a sharply peaked spectral response function. This assumption means we expect a superconducting qubit designed to function as a quantum sensor could have a substantial dynamic range, perhaps equal or better than High-Purity Germanium (HPGe)..

The qubits we use are superconducting transmons. They consist of two floating metallic planes connected by a Josephson junction. The qubit can be excited from the ground state by applying a microwave pulse that induces an oscillation of charge between the two plates. Owing to the non-linearity of the Josephson junction, energy level transitions are non degenerate.[1,2] The qubit state is measured through the dispersive shift it imparts to a coupled harmonic resonator (a readout resonator), in this case a coplanar waveguide resonator. The resonant frequency of the readout resonator is measured by homodyne detection and digitized. By ensuring that this state-dependent shift is readily resolved, single shot readout of the qubit is enabled.

A quantum sensor as we propose may be expected to have sensitivity on the millimeter length scale due to phonons propagating energy deposited by absorbed radiation across the device with the qubit coherence sensitive

Further author information: (Send correspondence to M.L.F.)
M.L.F.: E-mail: mlfreem@sandia.gov, Telephone: (505) 845-8488

to this propagated energy.[3] This situation is in contrast to superconducting tunnel junctions which are only sensitive to direct hits on an absorber that is typically on the micrometer scale.[4]

HPGe detectors, for example, typically require cryogenic operation at the boiling point of liquid nitrogen (77 K).[4] Our quantum sensor based on a superconducting qubit must be operated at a temperature well below the superconducting gap. Typically we operate our superconducting qubits at a temperature of 10 milliKelvin. As such it is reasonable to expect that a quantum sensor made from transmon qubits will have lower dark counts than HPGe sensors.

2. EXPERIMENTAL

2.1 Microfabrication

We fabricate transmon quibts on high purity instrinsic float zone silicon wafers with resistivity greater than 20 kOhm cm. Thin film Al is e-beam evaporated and patterned to form the readout resonators and the transmon qubit. The Josephson junctions were fabricated using the standard shadow evaporation technique and controlled exposure to oxygen to create an Al/AlO_x layer stack. The devices were then thermally anchored to a dilution refrigerator and cooled to 7 mK.

2.2 Design

Previous measurements of ionizing radiation on superconducting qubits have focused on the potential impact to quantum information processing.[5,6] These reports have primarily been concerned with the negative effects of radiation on coherence and the correlated errors it engenders. We are focusing on developing transmons as detectors, and so to better characterize a transmon's response to radiation, we are proposing to measure ionizing radiation from a source external to the cryostat. As shown in Fig. 1, the quantum sensor, a transmon, will be located near the bottom of the still shield of the dilution fridge. The source will be located directly opposite the quantum sensor (transmon) outside the vacuum jacket and at room temperature. With this configuration we can change the level of incident radiation by adjusting the spacing between the transmon and the source. We will be able to easily go between measurements with and without radiation for comparison. Nor will we need to cycle the system to change the radiation source.

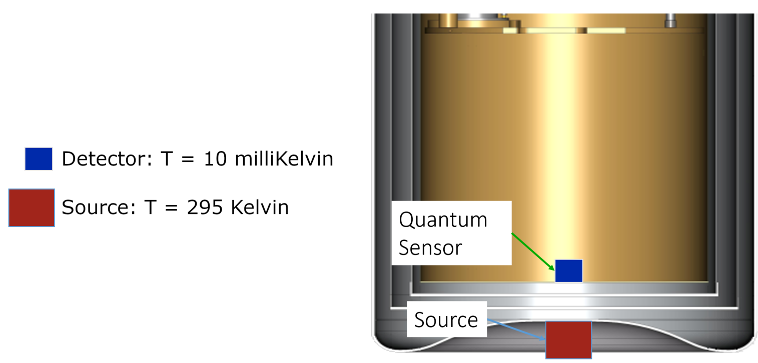

Figure 1. This figure illustrates our intended detection setup. The ionizing radiation will be generated by a source outside the cryostat. This configuration allows us to control both the exposure duration by removing the source and exposure intensity by the height of the source. This approach contrasts with earlier works in which the radiation source was installed inside the cryostat near the quantum device, limiting exposure control to natural radioactive decay.[5] As well as experiments that measured radiation of environmental origin[6] where radiation dosage was limited to an active source.

3. MEASUREMENT

Qubits are characterized by several measurements. The time to transition from the first excited state to ground (T_1) measures the lifetime of the qubit, the dephasing time (T_2) measures the coherence, and Rabi oscillation decay measures a combination of (T_1) and (T_2). Ionizing radiation is expected to lower coherence times,[3, 5–7] e.g., due to quasiparticles transiting the junction. Thus, a straightforward detection mechanism would be to look for a reduction in the probability of the device being in the excited state after a set delay time in a T_1 or T_2 measurement, or after a set pulse duration in a Rabi measurement. Figure 2 illustrates the Rabi case. Figure 2a) is a simulation of how a Rabi oscillation would be expected to decay with and without radiation. Figure 2b) is experimental data taken from one of our devices, showing a fit to the Rabi oscillations and the decay envelope. To decrease measurement time a single point such as an oscillation peak could be measured and compared with and without radiation.

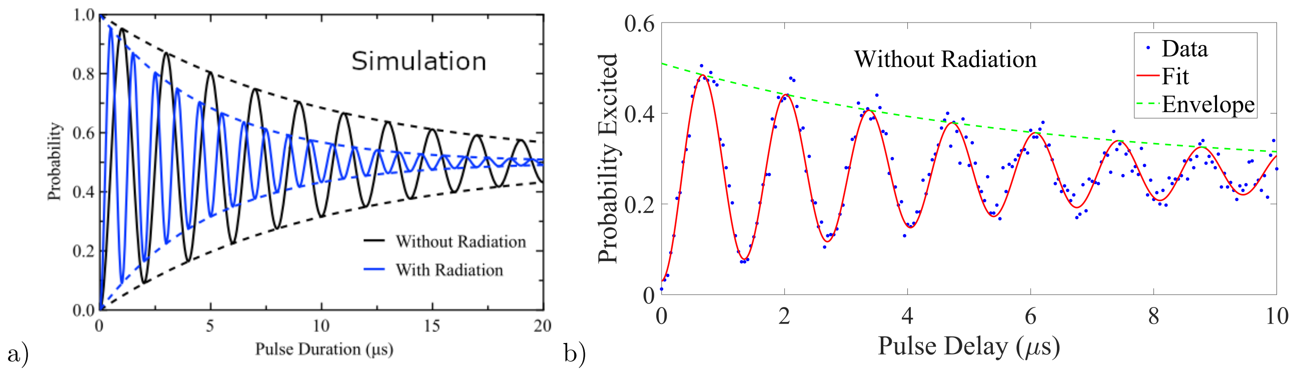

Figure 2. a) A simulation containing the non-irradiated fitted decay envelope in black and a radiation simulated envelope in blue. b) Data taken showing Rabi oscillations. The blue dots are experimental data, the red solid line is a fit to the data, and the green dashed line is the decay envelope to the fit. One possible avenue of detection could be a reduction in coherence times such as the Rabi decay envelope, shown as the green dashed line in experimental data. One problem with measuring a quantum device is that measurements can take longer than the lifetime of the response to ionizing radiation. To work around this temporal limitation a single point in a coherence measurement could be sampled, such as a peak along the decay envelope.

In summary we seek to utilize superconducting transmon qubits for the detection of ionizing radiation. We plan to use a radiation source positioned outside the cryostat allowing adjustments of the incident radiation flux without thermal cycling to decrease the time needed to test sensor (transmon) designs. We expect the effect of radiation to manifest as a reduction in excitation probability of T_1, T_2, and Rabi measurements.

ACKNOWLEDGMENTS

This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government. This article has been authored by an employee of National Technology & Engineering Solutions of Sandia, LLC under Contract No. DE-NA0003525 with the U.S. Department of Energy (DOE). The employee owns all right, title and interest in and to the article and is solely responsible for its contents. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this article or allow others to do so, for United States Government purposes. The DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan https://www.energy.gov/downloads/doe-public-access-plan .

REFERENCES

[1] Koch, J., Yu, T. M., Gambetta, J., Houck, A. A., Schuster, D. I., Majer, J., Blais, A., Devoret, M. H., Girvin, S. M., and Schoelkopf, R. J., "Charge-insensitive qubit design derived from the Cooper pair box," *Phys. Rev. A* **76**, 042319 (Oct. 2007). Publisher: American Physical Society.

[2] Krantz, P., Kjaergaard, M., Yan, F., Orlando, T. P., Gustavsson, S., and Oliver, W. D., "A quantum engineer's guide to superconducting qubits," *Applied Physics Reviews* **6**, 021318 (June 2019).

[3] Martinis, J. M., "Saving superconducting quantum processors from decay and correlated errors generated by gamma and cosmic rays," *npj Quantum Information* **7**, 90 (June 2021).

[4] Knoll, G. F., [*Radiation Detection and Measurement*], Wiley, 4th ed. (2010).

[5] Vepsäläinen, A. P., Karamlou, A. H., Orrell, J. L., Dogra, A. S., Loer, B., Vasconcelos, F., Kim, D. K., Melville, A. J., Niedzielski, B. M., Yoder, J. L., Gustavsson, S., Formaggio, J. A., VanDevender, B. A., and Oliver, W. D., "Impact of ionizing radiation on superconducting qubit coherence," *Nature* **584**, 551–556 (Aug. 2020).

[6] McEwen, M., Faoro, L., Arya, K., Dunsworth, A., Huang, T., Kim, S., Burkett, B., Fowler, A., Arute, F., Bardin, J. C., Bengtsson, A., Bilmes, A., Buckley, B. B., Bushnell, N., Chen, Z., Collins, R., Demura, S., Derk, A. R., Erickson, C., Giustina, M., Harrington, S. D., Hong, S., Jeffrey, E., Kelly, J., Klimov, P. V., Kostritsa, F., Laptev, P., Locharla, A., Mi, X., Miao, K. C., Montazeri, S., Mutus, J., Naaman, O., Neeley, M., Neill, C., Opremcak, A., Quintana, C., Redd, N., Roushan, P., Sank, D., Satzinger, K. J., Shvarts, V., White, T., Yao, Z. J., Yeh, P., Yoo, J., Chen, Y., Smelyanskiy, V., Martinis, J. M., Neven, H., Megrant, A., Ioffe, L., and Barends, R., "Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits," *Nature Physics* **18**, 107–111 (Jan. 2022).

[7] Wilen, C. D., Abdullah, S., Kurinsky, N. A., Stanford, C., Cardani, L., D'Imperio, G., Tomei, C., Faoro, L., Ioffe, L. B., Liu, C. H., Opremcak, A., Christensen, B. G., DuBois, J. L., and McDermott, R., "Correlated charge noise and relaxation errors in superconducting qubits," *Nature* **594**, 369–373 (June 2021).