Spectroscopy and coherent control of defects in superconducting films and qubits

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Introduction

A large variety of microfabricated devices suffer from structural defects which appear in disordered materials such as surface oxides, insulating dielectrics, layer interfaces and tunnel barriers. When a single atom or a small group of atoms can tunnel between two configurations, parasitic two-level systems (TLS) are formed which have excitation energies up to ~1K. These TLS couple by their electric and mechanical dipole moments to their hosting device, where they create noise and decoherence that affects i.a. kinetic inductance detectors (MKIDs), field-effect transistors (FETs), single-electron transistors (SETs), superconducting electronics such as SQUIDs, resonators and qubits, and even nanomechanical resonators. Mutual coupling between TLS has been conjectured to explain various anomalies of glasses, and was recently suggested as the origin of low-frequency noise in superconducting devices. A better understanding of TLS properties and their nanomechanical origins is thus of widespread importance in order to improve the performance of such devices.

Methods

We utilize a superconducting phase qubit as a tool to directly observe and manipulate TLS residing in a Josephson tunnel junction, where the large electric field amplitude couples individual TLS strongly to the qubit. The quantum states of TLS are directly manipulated using resonant microwave pulse sequences, and are read out by swapping them with the state of the qubit to make it accessible to measurement [1]. In order to tune the TLS' asymmetry energy, we apply mechanical strain to the qubit chip by means of a piezo actuator [2]. This allows one to perform a novel kind of defect spectroscopy which results in a detailed view onto the TLS distribution and provides evidence of their mutual interactions [3].

Results

Figure 1 gives an example of our TLS spectroscopy, where the resonance frequencies of individual TLS are tuned by strain and tracked with the qubit in a frequency range between 6 and 10 GHz. Anomalies such as a non-hyperbolic strain-dependence and telegraphic switching provide first clear evidence of mutual TLS interactions. Using conditional multi-pulse spectroscopy, we were able to map out the four-level structure of a system comprising two coherently coupled TLS [3]. From a study of TLS decoherence rates as a function of mechanical strain [4], we explore their interactions with the background bath of thermally fluctuating TLS and with discrete phonon modes. Moreover, we probe the interaction between TLS and BCS-quasiparticles (QPs) by generating QPs thermally or injecting them electrically, and observe the expected linear increase of TLS decoherence rates with QP density. We will also briefly discuss our current experiments where we couple a superconducting transmission-line resonator strongly to individual TLS.

Conclusion

We demonstrate the power of superconducting qubits for studying the quantum physics of individual atomic-sized defects in disordered layers. Since the detrimental effects of TLS affect a large variety of microfabricated devices, it is vital to understand the TLS' microscopic origin in order to avoid their formation during sample fabrication. In studying the interactions of TLS with electrons, phonons, strain and other TLS, we seek to shed light from various angles onto the rich but elusive physics of individual defects.

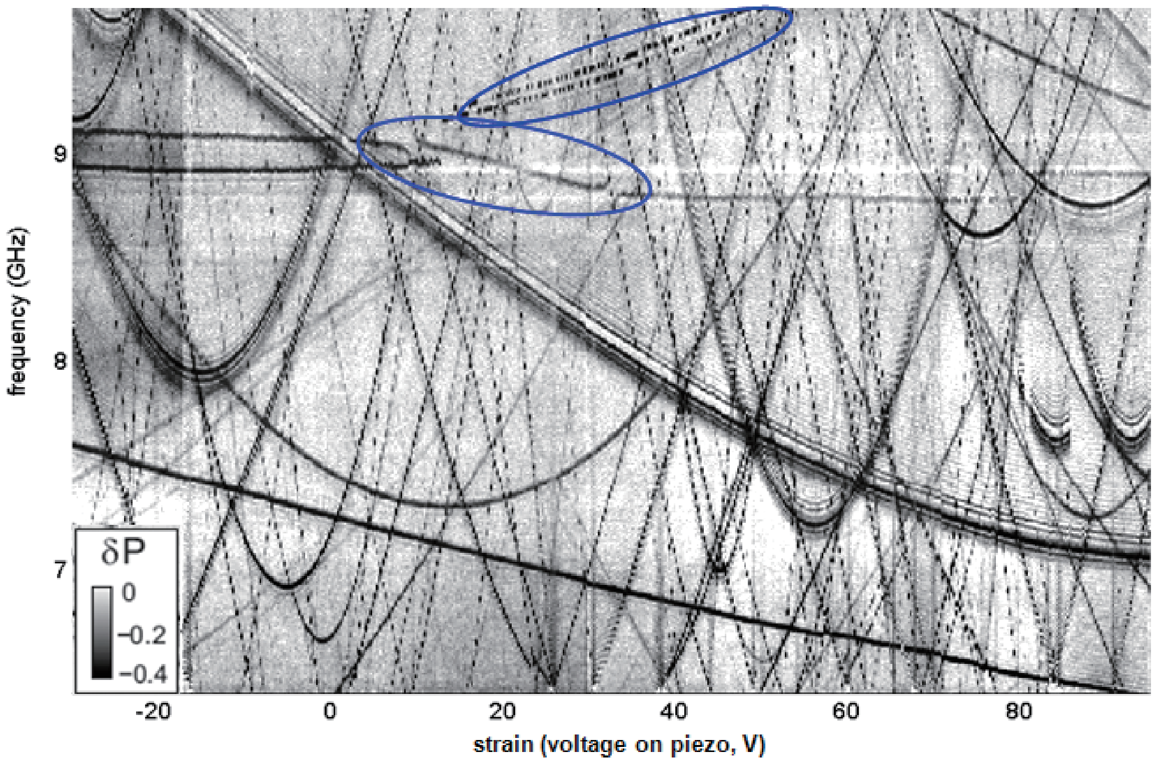

Figure 1: TLS spectroscopy, showing the resonance frequencies of strain-tuned individual TLS as dark traces. Encircled are anomalies which provide evidence of mutual coupling between TLS.

References

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Jürgen Lisenfeld received his Ph.D. in 2007, studying superconducting phase quantum bits in the group of Prof. Alexey Ustinov at University of Erlangen, Germany. Since 2008, he has worked as a postdoc at the Karlsruhe Institute of Technology (KIT) in Karlsruhe, Germany, where he began to investigate individual tunneling defects in superconducting circuits. From 2010 to 2011, he joined the Quantum Transport Group lead by Prof. Hans Mooij at TU Delft in Delft, The Netherlands, working on coupled flux qubits and Josephson bifurcation amplifiers. His current project is devoted to the development of an universally applicable detector and quantum interface for material defects in arbitrary materials.