Investigating and using Solid State Quantum Technology for Astroparticle detection

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Abstract: *Low temperature (< 1 K) solid state devices are ideal playgrounds to probe quantum effects: electron-phonon or electron-electron interactions, superconductivity, many body physics can, for instance, be probed by electronic transport, specific heat, thermal conductivity or out-of-equilibrium thermodynamics measurements. We propose to design and study the properties of highly tunable quantum materials that can be used as building bricks of cold quantum electronics and sensors sensitive to the quantum limit (single-photon detectors).*

Introduction

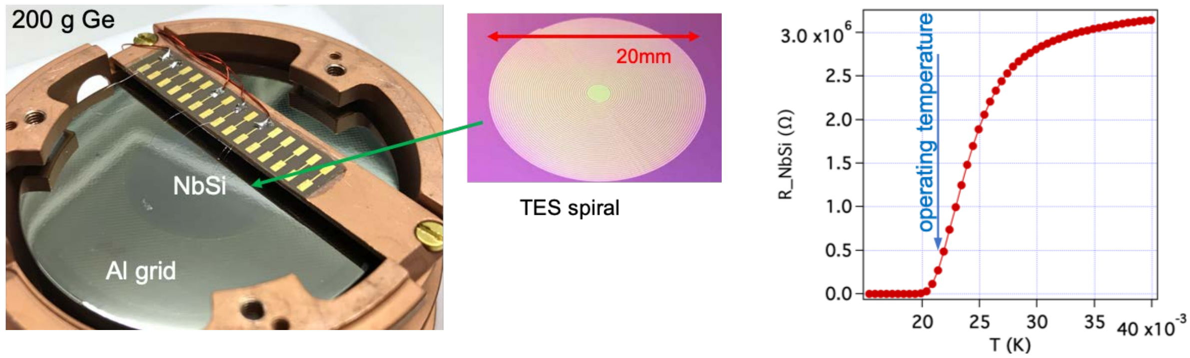
Solid state physics has been the basis for most of the currently existing quantum technology, be it through the development of semiconductors- and superconductors-based electronics or the functionalization of oxides. Indeed, these solid state systems have tunable properties (electrical and thermal conductivity, magnetic properties, dielectric characteristics, collective excitation modes,...) that makes them very versatile for applicative purposes. This amounts to exploring the phase diagram of these systems through the application of an external parameter (temperature, magnetic field, electric field, electromagnetic excitation,...).

In **IJCLab**, the **Astroparticle Solid State Detectors group** (ASSD) has been working at the interface of solid state physics and Astroparticle detection for more than 30 years now. The founding idea of the group is to use state-of-the art condensed matter developments to design innovative detectors for dark matter search (Edelweiss experiment), neutrino physics (CUPID and CROSS collaborations), Cosmological Microwave Background investigation (QUBIC collaboration) amongst others.

We here describe our current involvement and future plans.

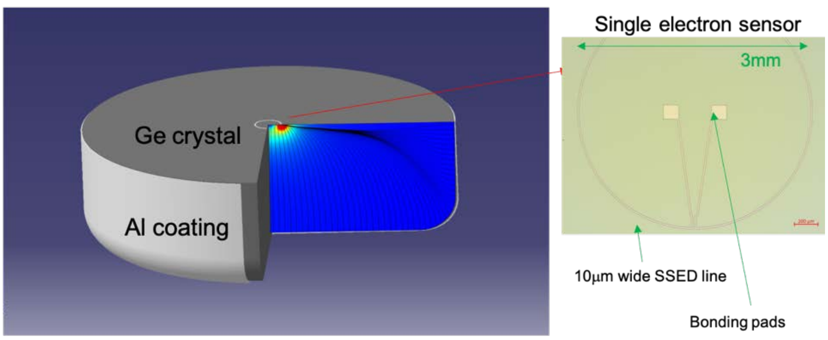
Superconductor-based detectors: Bolometers

There is an intense experimental worldwide activity devoted to single particle and photon detection using sub-K temperature devices. Reaching the quantum and thermodynamic limit of such detectors is very challenging and requires innovative state-of-the-art sensor technology. In the framework of projects related to dark matter research (EDELWEISS, IAXO) and neutrino physics (CUPID, RICOCHET), the ASSD group at IJCLab is developing massive bolometers based on superconducting structures that act as phonon, charge or light sensors. An important R&D was undertaken involving Astroparticle detectors equipped with several prototype designs of transition-edge sensors (TES). Once optimized, these sensors allow to reach the ultimate thermodynamic limit of the bolometer temperature fluctuations, and opens the way to quantum-limited detection.



Several TES-detectors were deployed in the EDELWEISS cryostat at the Modane underground laboratory (LSM) between 2018 and 2020 for direct dark matter research. These prototypes were based on 200 g high purity Ge crystals equipped with a Nb-Si superconducting alloy and simultaneous measurement of the charge and heat signals. Their energy resolution was in the 10 eV range.

More recently the group has proposed an innovative solution for single-charge detection on Ge and Si massive crystals. We develop a technology similar to superconducting single photon detectors (SSPD) to measure the Joule heating produced by the drift of the carriers in a Ge or Si crystal (Neganov-Luke effect). This is a unique method that should permit to measure single electron excitations produced by a particle interaction depositing an energy as low as 1 eV into a massive semiconducting crystal. The ultimate threshold attainable by these sensors is quantum limited by the electronic energy gap of the Ge or Si semiconductor (respectively 0.7 and 1.2 eV). Combining this solution with an efficient calorimetric sensor is a powerful way to get background free eV-threshold detectors needed for direct dark matter research and coherent neutrino-nucleus elastic scattering.

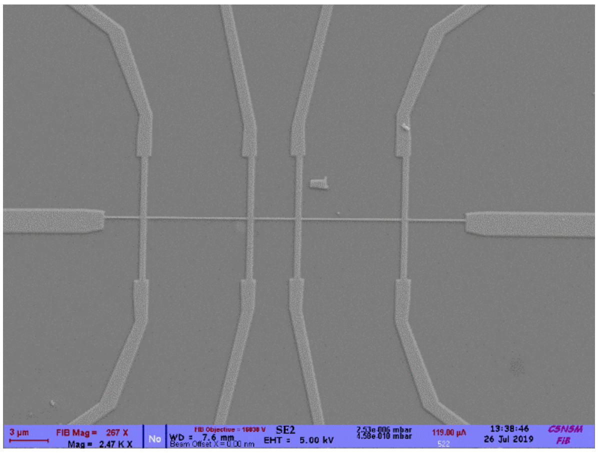


Design of a single electron Ge detector and micro-photography of a NbSi superconducting thin line sensor (10 µm width) developed at IJCLab.

Nanoscale Superconducting Devices

Advances in fabrication techniques have led to the development of superconducting devices capable of detecting single photons [1]. The working principle is based on the existence of an energy gap at the Fermi level below the superconducting critical temperature. An incident particle arriving with an energy greater than the characteristic binding energy of Cooper pairs generates a noticeable change in the resistivity.

Development of superconducting devices requires an in-depth understanding of solid-state physics. Different phenomena which need to be taken into account are the effects of electron-electron and electron-phonon interactions, energy dissipation due to quasiparticles and thermalization between the system and its environment. The sensitivity of measurements relies greatly on the optimization of device geometry and properties of the material chosen.

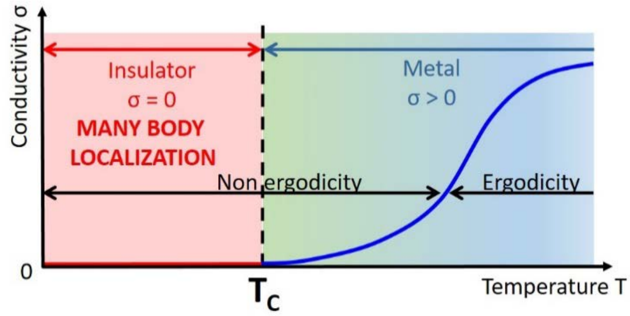


A nanowire of NbSi fabricated at IJCLab. The typical width of the conducting channel is 100-200 nm.

Members of the group ASSD at IJCLab are experienced in developing superconducting devices over many years. Our research has been based on various kinds of superconducting materials, e.g. NbSi, Al, YSi. We plan to design new kinds of devices using nanofabrication techniques to scale down the dimensions up to few tens of nanometers. This is expected to enhance the sensitivity of the devices. In recent times, theorists have suggested that superconductors may be employed not just for photons, but even for detection of dark matter using the Josephson effect [2]. It is therefore interesting to study different types of superconducting devices at the nanoscale to explore their properties and potential for application as detectors of particles.

Disordered superconductors as a playground for Many-Body Localization

This prospective is part of the CP-Insulator project objectives.



Ten years ago, the theory of disordered quantum systems has made an important advance by proving that disordered many-body systems decoupled from any external bath (e.g. phonons in solids) might acquire very unusual properties related to a new phenomenon called many-body localization (MBL) [3-5]. In the context of disordered interacting electrons, the MBL implies the absence of any macroscopic transport and the theoretical analysis indicates that in such systems a new kind of insulating state is expected with strictly zero conductance (σ) even at non-zero electronic temperatures below a well-defined critical temperature T_c. More recent works [6,7] discovered an intermediate regime with non-ergodic dynamics similar to that of glassy systems, which might appear before full MBL is reached at T_c. These phenomena are of practical importance since they would allow the design of quantum computing architectures that bear an intrinsic protection against noise (see for instance [8]).

Experimental studies of MBL are clearly in their infancy. The main difficulty of experimental realizations in condensed matter systems is the need to suppress the coupling to the environment, which is crucial for the appearance of MBL. This requirement makes most well-known experimental platforms unsuitable for the study of MBL. For instance, disordered semiconductors are not adequate for MBL due to a significant electron-phonon coupling and the practical difficulty of studying them in the strongly localized regime where MBL is expected. One of the most promising platforms for such study is provided by the class of disordered superconductors that retain a pairing gap in their high disorder insulating phase, meaning that the insulating phase is actually a bosonic phase where Cooper pairs are localized due to disorder [9]. The reason for this is that large values of the single particle gap suppress the direct electron-phonon relaxation mechanism, which should make the observation of MBL in such materials possible. Practically, we expect to observe anomalous temperature dependence of the transport properties such as the conductivity in the vicinity of the Superconductor-Insulator Transition (SIT).

One promising candidate to observe MBL is a-Y_xSi_{1-x} which has previously been known to show a strong electron-phonon decoupling. Our aim is to characterize this system in the 2D limit through the SIT through very low temperature (< 1 K) electronic transport measurements and look for signatures of a MBL state. This work will be done in collaboration with theoretical and experimental groups in Grenoble (Institut Néel) and Paris (LPEM, LPTHE) in the framework of the funded CP-Insulator ANR project.

On the longer run, we will engage in thermal conductivity measurements to experimentally prove that heat the electronic and phononic baths indeed are decoupled, thus giving rise to potentially interesting applications, for instance for local cryogenic cooling or information transport.

References:

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