Superconducting Diamond as a platform for quantum technologies

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Abstract. We present some of the anomalous transport features that have recently been observed in boron doped diamond, these include the re-entrant Bosonic Insulating peak, Zero Bias Conductance anomaly and non-linear magnetoresistance. The features, related to confined condensate phase and bound states, are expected to interesting for novel device functionality particularly in low dimensional device elements such as superconducting resonators and phase slip qubits. The fabrication techniques required to produce such device elements are also discussed, including our preferred method of He ion source focused Ion beam (FIB) patterning.

1. Introduction

Superconductivity in boron doped diamond was discovered in 2004 and has since been the topic of numerous investigations into unconventional superconductivity. Having studied the superconducting boron doped diamond system we have identified a number of anomalous features related to the reduced dimensionality of the system. Such features include re-entrant superconductivity due to bosonic insulating phase [1], anomalous Hall effect [2], a Berezinski-Kosterlitz-Thouless (BKT) transition [3] and pronounced zero bias peak in the differential conductance [4]. Due to the intrinsic insulating properties of diamond, we have analyzed these features in terms of charging effects, in particular we have shown the possibility of a Charge-Kondo effect leading to the observed BI resistance peak, as well as evidence for a Charge-BKT transition. These features are related to condensate confinement to the nanocrystalline grains, interfacial bound states and topological excitations. With the advancements of superconducting quantum technologies, it is becoming increasingly important to enhance device functionality, one particularly successful direction is that of Transom type qubits [5], where a quantum system is coupled to a microwave transmission line, enabling easier control and readout for logic operations. Interestingly recently hybrid technologies have been envisioned whereby device elements containing exotic quantum states such as solitons [6], Majorana fermions [7] and other bound states [8] are coupled to Transmon type systems. Such hybrid systems are interesting as they offer the possibility of topologically protected quantum computing. Due to the anomalous transport features identified in boron doped diamond, we believe this system is an ideal platform for such next generation quantum technologies.
Figure 1. a) Re-entrant resistivity in the form of a so called Bosonic Insulating phase has been observed. This phase is generally followed by a temperature independent resistance saturation, a possible indication of phase slip events. b) Magnetoresistance of the superconducting diamond films also show non-linear peak structures similar to the field induced superconductor to Insulator transition observed in other superconducting systems, c) The differential conductance of the films demonstrate a pronounced peak at zero bias, an indication of inter-granular bound states. d) Super-linear behavior is observed in the current voltage sweeps, these follow the expected exponential scaling for a BKT transition.

2. Experimental results

A. Anomalous transport features

The superconducting boron doped diamond system has presented a unique system where carrier correlations, phonon modes and exotic phases have a huge implication on the transport of the system. The nanocrystalline subclass of this material has shown to be even more exciting, with a number of anomalous transport features not observed in the single crystal analog. The effects of electron confinement to the individual grains has led to a number of phenomena such as dimensionality crossovers [9] in the fluctuation regime, confinement of the superfluid state [10], inhomogeneous distribution of order parameter [11] and the observation of zero bias conductance and the Bosonic insulating phase [1]. As shown in figure 1 (a), the system can be tuned from the superconducting state to one of a pronounced insulating state with resistance values more than the normal state resistance. This resistive peak can be suppressed by applying magnetic fields [1,4] and measurement bias above a minimum threshold value [4]. There have also been reports of the re-entrant effect being a result of a Charge-Kondo effect related to the degeneracy of the carriers [4]. The tunability of this effect make it particularly interesting for device applications where the transition can be easily induced through applied field or measurement current. A nonlinear magnetoresistance is also observed, figure 1 (b), this features bears sticking similarity to the magnetoresistance observed in systems that exhibit either the disorder or field induced superconducting to insulating transition (localization of Cooper pair condensate). The ZBCP, figure 1 (c), is a strong indication of the existence of Bound States, likely due to lattice plain mismatch at the grain interface. Such bound states have before been observed in other type-2 superconducting systems and are generally related to Andreev type scattering events at the superconducting grain boundaries [12]. Finally one of the most intriguing effects in this system is the signature of BKT transition in the power law scaling of the current voltage characteristics (figure 1 d). This feature has also been confirmed through resistance temperature analysis [3]. This is particularly interesting as the BKT transition is restricted to 2D systems, thus the observation here further indicates grain junction properties dominate in this system.
B. Microstructure.

The microstructure of poly and nanocrystalline diamond has been studied due to the interesting properties of the grain boundaries [13]. It is well known that CVD diamond frequently shows twinning where the crystal symmetries of the twins have an effect on the properties of the grain boundaries. It has also been established that the surface termination (strong lattice miss match) of the diamond grain can lead to the formation of an extended $\pi^*$ orbital configuration because of hybridization of dangling bonds near grain boundary termination [14], heightened stress at the grain boundary region can induce surface states through a modification of the electronic energy of the so called frontier electronic orbitals [15]. All of these studies indicate that the electronic transport of granular diamond systems is greatly dependent on the grain boundary region and the interface between two grains, this becomes particularly interesting when considering the superconducting boron doped diamond system as granularity and boundary scattering/tunnelling events in superconducting systems can lead to interesting phenomena. This is well known for type-two superconducting systems such as the high $T_c$ cuprates where transport properties of the grain boundaries have been thoroughly investigated [16]. It is well known that such systems can exhibit zero bias resonances as shown in figure 1 (c). Thus the system supports a superlattice like structure (figure 2 a-c), which leads to the anomalous feature presented here.

C. Device Fabrication

Although diamond is not a common material for device fabrication, there are a number of conventional fabrication techniques that can be used for developing diamond-based electronics. These typically include reactive ion etching or Focused ion beam milling for patterning of device structures. In this work we investigate the incorporation of nano-structured boron doped diamond into Transmon type systems for hybrid qubits. The transmission line as well as grounding planes can be fabricated from monolithic boron doped diamond (figure 2 a & b). As mentioned previously, due to the strong confinement effects of this system, as well as the observation of bound states (possibly soliton in nature due to the observation of the BKT effect) low dimensional device structures such as nanowires and junction constrictions are of particular interest. This is because the condensate is unstable in such elements and trapping of the bound states or even observation of phase slip events are possible. Thus, this system may be of interest for phase qubits [17], which relies on the quantized motion of flux lines across a thin superconducting nanowire. The phase slip event occurs due to a point of instability along a very thin superconducting nanowire where the superconductivity breaks down locally, leading to a $2\pi$ phase change. This is generally controlled through an applied field; the energy level spacing of the qubit is thus dependent on the quantized flux number penetrating the loop. These type of device have been fabricated from other superconducting system showing resistive anomalies [18] some of the device elements under investigation are presented in figure 2 (c-d). These smaller structures are created using high resolution He ion beam milling (Zeiss-Orion FIB), which has the advantage of decreasing the chance of doping or contamination from conventional Ga ion source beam. Dual beam systems that operate with different ion sources are used for patterning of different scaled structure, using this method device element with dimensions down to a few nanometers are possible as well as larger structures up to millimeter scale.

3. Conclusion

We have highlighted some of the anomalous transport features of the superconducting boron doped diamond film, these include re-entrant Bosonic Insulating phase and zero conductance peaks due to intergranular bound states. These features may be valuable for next generation superconducting technologies particularly novel hybrid qubits. Useful device fabrication techniques are discussed, particularly focused Ion Beam milling which has proven capable of patterning some of the smallest diamond structures to date.

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Figure 2. a) High resolution TEM imaging has indicated a superlattice like structure of nanocrystalline grains with pronounced twinning. b) High energy grain boundaries with sharp lattice mismatch as well as definite c) 2D boundary regions have been observed. d) Using a combination of Ga and He ion patterning we have demonstrated both large scale patterning such as d) contact pads, conduction channels and e) co-planar waveguide resonators as well as more refined nano-scaled structures such as f) nanowires and g) phase slip loops.

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