Phase Transition Study of Superconducting Microstructures

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Abstract

The presented results are part of a feasibility study of superheated superconducting microstructure detectors. The microstructures (dots) were fabricated using thin film patterning techniques with diameters ranging from 50µm up to 500µm and thickness of 1µm. We used arrays and single dots to study the dynamics of the superheating and supercooling phase transitions in a magnetic field parallel to the dot surface. The phase transitions were produced by either varying the applied magnetic field strength at a constant temperature or changing the bath temperature at a constant field. Preliminary results on the dynamics of the phase transitions of arrays and single indium dots will be reported.

1 INTRODUCTION

Metastable superconducting devices, either made of a suspension of granules or consisting of thin film arrays, are presently under investigation for different applications like dark matter detection [1] or high spatial resolution x-ray imaging devices [2]. Experiments with single granules have shown that the strength of the superheating and supercooling fields depends on the crystalline structure and on the orientation of the granule with respect to the applied magnetic field [3]. The measured superheating field distributions of Superheated Superconducting Granule (SSG) detectors have standard deviations of the order of 15-20%. An order of magnitude improvement on the phase transition spread of
a collection of granules can be obtained if ordered arrays made of spherically
melted indium pads (PASS detector) are used [4].

The metastability of thin films has been studied in the past by several au-
thors using strips or square samples [6]. In particular, J. Blot et al. [7] inves-
tigated the superheating and supercooling transition of thin indium squares in
perpendicular and parallel magnetic fields at temperatures very close to $T_c$ with
susceptibility measurements. In the earlier experiments, the phase transition of
the whole array was measured without extracting informations on the behaviour
of single elements. To investigate the dependence of the metastable phase tran-
sitions on the granularity and on the geometrical order of the superconducting
detector elements, we are studying arrays made of aluminium and indium thin
disks (dots) exposed to perpendicular and parallel magnetic field. The readout
configurations used in our experiments allow us to detect the phase transition of
each element inside the array. Recent measurements of indium dots in perpen-
dicular magnetic field, with the readout coil integrated directly on the substrate,
are reported in Ref. [5]. Preliminary results on the dynamics of the phase tran-
sitions of arrays and single indium dots in a parallel field will be reported in
this paper.

2 EXPERIMENTAL PROCEDURE

We measured indium dots of cylindrical shape with a thickness of 1µm and diam-
eters between 50µm and 500µm. The films were fabricated at the IESS-CNR in
Rome on silicon substrates using electron-beam evaporation and patterned with
photolithography and lift-off technique. Scanning electron microscope analysis
have shown a granular structure of the indium film with a typical grain size of
2-3µm. The geometrical definition of the edges of the dots was dominated by the
film granularity. The experiments were performed in a pumped 4He cryostat.
The temperature was determined by measuring both the vapor pressure over the
4He bath and the value of a calibrated Allan-Bradley 105Ω resistor. The
investigated range of temperature was from 1.4K up to 2.1K. The temperature
regulation was done by adjusting the pumping power with a regulating valve and
by heating the 4He bath. The temperature stability was better than 10mK. The
samples were mounted at the end of a top-loading insert. The magnetic field
was produced by a superconducting Helmholtz coil placed inside the cryostat.
The homogeneity of the field was calculated to be within $10^{-3}$ in the volume
surrounding the sample.

We performed measurements applying the magnetic field at different angles
with respect to the dot surface. The angles were varied by turning the top-
loading insert and measured with a laser beam incident on a mirror placed on
the axis of the insert. The angular resolution of the setup was better than 0.03°.
To measure the change in flux due to the transition of a single dot, a one or
a three layer pickup coil was wound directly around the Si substrate as it is
shown in Fig. 1a. The coils were made of 63-84 turns of 25\(\mu\)m copper wire and wound under a microscope with the help of a micromanipulator. The precision of the wire alignment was better than 10\(\mu\)m. The distance between the dot surface and the windings of the coils was measured to be about 0.5\(\mu\)m. In a few samples, only some rows of dots were covered by the pickup coil as it is shown in Fig. 1b. In this configuration the measured change in flux of a dot covered by the pickup coil was higher compared to the one of a dot outside the coil. This allowed us to identify the row of the flipped dot. The coil was coupled to a current sensitive amplifier with a risetime of \(\approx 80\)ns and a gain of 2000.

3 MEASUREMENTS

Thin superconducting dots in a parallel field have superheating phase transitions (flip) characterized by a fast transition time, as it is shown in Fig. 2a for a 300\(\mu\)m wide and 1\(\mu\)m thick In-dot at 1.4K. The speed of the transition is comparable to the measurements with superconducting granules [8]. When the sample is slightly tilted with respect to the magnetic field, the flip becomes broader, as it is shown in Fig. 2b. The fragmentation of the signal is an indication that the nucleation of the superheating transition does not happen at once but rather in steps. This is due to the increased effective field strength at the upper and lower edges of the dot when the sample is tilted [9]. As a result the field penetration starts locally. The angle at which the flip signal starts to be broad depends on the diameter of the dot but not on the structure of the superconducting film. Typical angles are \(\pm 2.5^\circ\) for a 50\(\mu\)m wide dot and \(\pm 0.25^\circ\) for a 300\(\mu\)m sample. The speed of the supercooling transition (flop) was measured to be \(\sim 1\mu\)s for a 300\(\mu\)m wide dot. It does not significantly depend on the sample orientation in the range of angles from \(0^\circ\) up to \(\pm 6^\circ\).

The distribution of the superheating and supercooling fields of the arrays was measured by cycling the magnetic field at a constant temperature. In each cycle the field was changed with a constant ramping speed of 40 Gauss/s from zero up to 400 Gauss and then lowered to the zero value. We were able to observe the superheating and supercooling transition of each dot in the array. Typical flip and flop signals recorded with the sequence trigger function of a digital oscilloscope (LeCroy 9450) are shown in Fig. 3a for a 5x5 array of 300\(\mu\)m dots in a parallel field at 1.4K. The measurements were done using the position sensitive coil readout as shown in Fig. 1b. The area filling factor of the sample was 28\% and the dots can be considered as isolate elements. In each cycle the same sequence of signals was identified. In agreement with previous measurements on collections of superconducting granules [10], it turned out that the superheating and supercooling fields are two independent properties of each dot. The penetration of the magnetic field in dots with low superheating field is probably induced by geometrical defects which locally enhance the strength of the applied field. The time evolution of an early and a late flip signal within a
cycle is shown in Fig. 3b. The transition time of the early flipping dots is longer because the penetration of the field starts locally. Dots with higher superheating fields have less surface defects and the field penetration is more symmetric and faster. The amplitude of the flip signals is due to the position of the dots with respect to the pickup coil and to the speed of the superheating phase transition. The nucleation of the supercooling transition is not influenced by such magnetostatic effects. The transition speed was always $\sim 1\mu$s and the amplitude modulation is only due to the dot position with respect to the pickup coil.

The measured superheating and supercooling distributions of a 20x20 array made of 100$\mu$m indium dots at the temperature of 1.4K are shown in Fig. 4. The area filling factor of the array was 65% and all the dots were covered by the pickup coil. To increase the statistics, the measurements were done in 500 consecutive cycles. The spread of the distributions was evaluated with a gaussian fit of the data. Standard deviations of 2% were found in both superheating and supercooling field distributions. The observed spread is an order of magnitude lower than the typical values ($\sigma=15\textnormal{-}20\%$) measured in collections of granules. This could be related to the polycrystalline structure of the indium film.

To investigate magnetic interactions among dots, we performed measurements on a 10x18 array made of 50$\mu$m dots with an area filling factor of 68%. The measurements were done with the array parallel and tilted by 1.5$\degree$ with respect to the applied magnetic field. In Fig. 5 the two sequences of flipping signals within a cycle are shown. When the array is parallel to the field multiple flips were observed, especially at the end of the cycle. Multiple flips were identified by comparing the measured change in flux to the value associated to a single dot transition. Multiple flip signals start to split up in single flip signals when the array is tilted by $\geq 0.5\degree$. The time evolution of the transition signal is shown in Fig. 5c for the same event in a parallel field and at 1.5$\degree$. The contribution of three dots to the flipping signal is clearly visible when the array is tilted. The same sequence of signals was found in consecutive cycles also when the magnetic field was ramped at different speeds. Multiple flips were not observed in arrays with smaller area filling factor.

The occurrence of multiple flips in highly packed arrays can be interpreted as a magnetic avalanche effect. The density of the field lines changes locally when a dot undergoes a phase transition. This effect increases the strength of the magnetic field near a neighbour dot, producing another phase transition. Such a mechanism can propagate to other elements of the array. We measured a phase transition multiplicity up to four in a parallel field. When the array is tilted the magnetic coupling among dots is less strong.

4 CONCLUSION

The measured superheating and supercooling distributions of indium dot arrays have spreads one order of magnitude lower than the typical values measured in
collections of granules. We are planning a more systematic study on dot arrays made of films with different granularities to investigate if the smearing of the superheating and supercooling fields can be reduced by using polycrystalline films. We measured the occurrence of multiple flips in highly packed arrays. The use of such a mechanism as a possible signal amplification in bidimensional superheated superconducting detectors is under investigation.

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Figure captions

1. a) Schematic sketch of the pickup coil arrangement used in the measurements. b) Position sensitive pickup coil over a 5x5 array.

2. Time evolution of the superheating transition signal $V(t)$ (upper curves) and of the corresponding change in flux $\Phi(t)$ (lower curves) for a $300\mu$m wide and $1\mu$m thick In-dot at 1.4K. a) Parallel field. b) Dot tilted by $0.8^\circ$. 

5
3. a) Sequence of flip (positive) and flop (negative) signals of a 5x5 array made of 300µm dots at 1.4K. The measurements were done in a parallel field and two consecutive cycles are shown. b) Time evolution of the flip transitions $V(t)$ (two upper curves) and corresponding change in flux $\Phi(t)$ (lower curves) for an early and a late event within a cycle.

4. a) Supercooling and b) superheating distributions measured in 500 consecutive cycles with a 20x20 array made of 100µm dots. The standard deviations of the distributions are 2.05% (supercooling) and 1.87% (superheating).

5. a) Sequence of flipping signals in a parallel field and b) tilted by 1.5°. c) $V(t)$ for a flip with multiplicity of 3 in a parallel field (upper line) and for the same event with the array tilted by 1.5° (lower line)