RADIATION HARDNESS OF INDIUM OXIDE FILMS IN THE COOPER-PAIR INSULATOR STATE

by

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This paper investigates possible radiation effects in the Cooper-pair insulator state of indium oxide films. Radiation effects are predicted on the basis of Monte Carlo simulations. Results of a combined theoretical and numerical analysis suggest that radiation-induced changes in the investigated films could significantly affect their current-voltage characteristics, and that a transition to a metallic state is possible, due to radiation-induced disruption of the fine-tuned granular structure. Dissociation of Cooper pairs, caused by both the incident radiation and the ions displaced within InO_x films, can also destroy the conditions for this specific insulating state to subsist.

Key words: indium oxide, Cooper-pair insulator, radiation damage, Monte Carlo simulation

INTRODUCTION

Cooper-pair insulators (CPI) are materials that exhibit superconducting behavior, but under specific conditions (regarding film thickness, bias voltage, applied magnetic field, and presence of magnetic impurities) act as insulators with thermally activated Cooper pairs as charge carriers [1-3]. Such behavior has been observed in thin films of indium oxide [4-7]. This insulating phase is characterised by a granularlike structure, consisting of superconducting droplets (*i. e.* islands of localized Cooper pairs) distributed throughout a matrix of normal material [8-11]. Under suitable conditions, the islanding of Cooper pairs appears spontaneously in the material as a consequence of increased disorder. The phenomenon of superconducting materials turning into insulators is therefore often regarded as a disorder-driven superconductor-insulator transition [10-13].

The granular structure of a CPI can be modeled by a two-dimensional Josephson junction array (2D JJA) [1, 14]. It is a system consisting of small superconducting islands, each coupled to its nearest neighbours by Josephson weak links. Each junction is characterized by the Josephson coupling energy, $E_J = \hbar I_c/(2e)$, where I_c being the Josephson critical current and e the elementary charge, as well as by charging energies E_c and E_{c0}, related to inter-island capacitance and capacitance to ground (substrate), respectively. The charging energy E_c is the energy needed for a Cooper pair to be transferred between neighbouring islands.

Extensive studies of the conditions under which the stated materials act as either superconductors or insulators at temperatures below 1 K have shown that, in terms of the JJA model, the insulating phase emerges only when the conditions determining the degree of disorder make the charging energies larger than the coupling energy (E_c, $E_{c0} > E_J$), with the superconducting gap still exceeding the inter-island charging energy ($\Delta > E_c$) [5, 6]. At the application of an external voltage, in addition to local phase coherence and spatial confinement of Cooper pairs, wave function phase synchronization of all Cooper pairs in the JJA occurs, giving rise to a collective current state. Dc Josephson current couples the phases of adjacent junctions, so as to provide minimal power dissipation in the array. This establishes a global phase-synchronized state, and transport occurs as a simultaneous thermal activation of Cooper pairs through the whole array [1, 2]. Resistance follows an Arrhenius-like temperature dependence.

The uncertainty principle applied to a Josephson junction gives $\Delta\varphi\Delta n$ 1, where φ is the phase difference across the junction, and n is the number of Cooper pairs transferred through the junction.

Detailed physical explanation for the insulator-superinsulator transition is based upon energy relaxation from the tunneling Cooper pairs not only to

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the phonons, but also to intermediate bosonic modes (electromagnetic or electron-hole excitations) [15]. Tunneling through mesoscopic junctions, such as those between superconducting islands in a 2D JJA, requires an exchange of energy between the tunneling charge carriers and some kind of excitation modes, to compensate for the difference in energy levels at junction banks. At low temperatures characteristic of the CPI phase, charge transfer is accompanied by a two-stage energy exchange. The tunneling Cooper pairs generate electron-hole pairs that serve as an environment exchanging energy with the tunneling current and then slowly losing it to phonons. At the nano-scale typical of the granular structure in InO films, the Coulomb interaction acquires a logarithmic dependence on the distance between charges.

This paper investigates the effects of ionizing radiation on the properties of the Cooper-pair insulator state of indium oxide films, by using numerical simulation of particle transport.

SIMULATION OF RADIATION TRANSPORT

Monte Carlo simulations of ion beams traversing InO films of different thickness (10 nm to 20 nm) were performed in the TRIM part of the SRIM software package [16]. The fact that TRIM calculations assume target temperature to be absolute zero makes it an appropriate tool for modeling radiation effects in the Cooper pair insulating state, which exists only at very low temperatures anyway, so that thermal diffusion and annealing of displaced atoms in the film can be neglected. Another approximation inherent in TRIM is that there is no build-up of radiation damage in the target, *i. e.* for each new incident ion the film is assumed to contain no damage produced by previous ions. Any assessment of the degree of radiation damage in the film is therefore an underestimation of the damage that a real ion beam would have caused. Since we were primarily interested in ion beam effects in superconducting islands within the granular structure of CPI, we used TRIM's calculation of ionization losses to estimate the scope of Cooper pair breaking in these islands, by substituting atom ionization energies with depairing energies in each of the investigated materials.

Simulations were conducted with ions chosen to represent certain well known radiation fields, such as those encountered in the space environment (hydrogen, helium, lead) [17, 18], or beams commonly used in ion implantation processes (phosphorus, boron, arsenic). Simulations were restricted to monoenergetic unidirectional beams, incident perpendicularly on the film surface. Beam energy was varied across typical energy spectra of different ion species.

Example plots obtained from the simulations are shown in figs. 1 and 2. Distributions of displaced indium and oxygen atoms in a 20 nm thick InO film irradiated by a beam of five hundred 10 keV boron ions are shown in fig. 1. Results in fig. 2 present ionization energy losses per unit depth by ions and recoils (displaced In and O ions) in a 20 nm thick InO film irradiated by a beam of five hundred 50 keV iron ions.

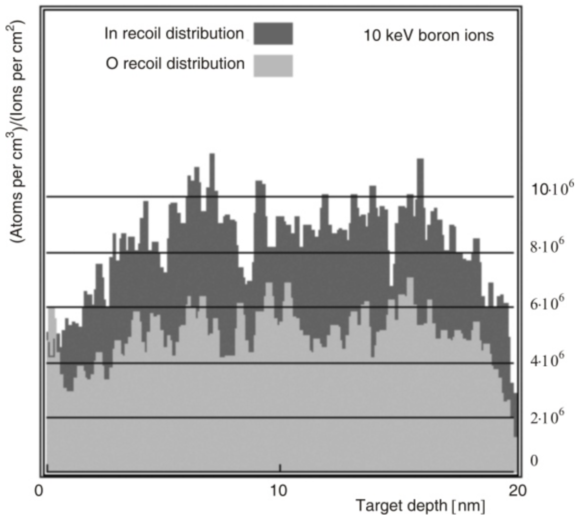

Figure 1. Distribution of displaced indium and oxygen atoms in a 20 nm thick InO film irradiated by a beam of five hundred 10 keV boron ions

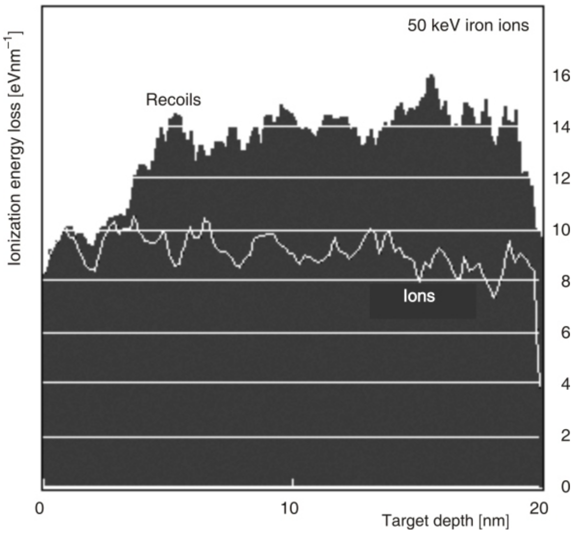

Figure 2. Ionization energy loss by ions and recoils (displaced In and O ions) in a 20 nm thick InO film for an incident beam of five hundred 50 keV iron ions

DISCUSSION OF THE POSSIBLE RADIATION EFFECTS

Owing to their small thickness, the investigated films are immune to high energy ions. Non-ionizing energy loss of high energy ions is low, and they traverse the films without deflection, causing inconsiderable damage [19-22].

Simulations of ion transport suggest, however, that for certain ion species there exist energy ranges in which a great number of atom displacements would occur in irradiated films. The number of atomic displacements is in direct proportion to the fluence of incident radiation, *i. e.* the number of particle histories followed in the Monte Carlo simulation. Space charge created by the displaced ions that finally take interstitial positions could affect the size of the Josephson junction charging energy E_c, which then changes the collective Coulomb barrier Δ_c. The low-bias ($eV \ll \Delta_c$) current-voltage dependence in the temperature interval $E_c < k_B T < \Delta_c$ is [1]

$$I \quad I_c \exp \quad \frac{(\Delta_c \quad eV)^2}{2\Delta_c k_B T} \qquad (1)$$

where I_c is the Josephson junction critical current. The change in the I-V curve, resulting from the radiation-induced change of E_c, is illustrated for indium oxide in fig. 3.

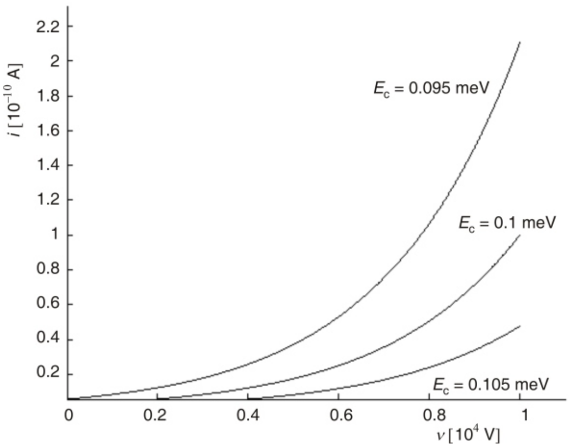

Figure 3. Indium oxide film I-V curves for three values of the Josephson junction charging energy E_c. The 5% change in E_c occurs due to the space charge of the displaced ions which become interstitials in the irradiated film

The stability of the investigated insulating state is dependent on the value of E_c, and only exists when $E_c > E_J$. If the radiation damage produced by ion beams is large enough to disrupt this condition, the thin film may revert to the ordinary metallic state.

Ionization energy losses by both the incident and the recoil ions observed in simulations point to a possible breaking of Cooper pairs in superconducting islands, that could destroy the insulating state during irradiation. With other conditions unchanged, this effect is expected to gradually vanish once irradiation ceases. The Cooper pairs may then reform and restore the insulating state.

CONCLUSIONS

In spite of the investigated indium oxide CPI films being immune to the passage of high energy ions, simulations of ion transport reveal that significant ionization, phononic excitation, and production of displaced atoms can be expected for some energies, fluences, and types of ions encountered in cosmic rays and used for implantation processes. Displacement damage, affecting primarily the value of inter-island charging energy in the 2D JJA that represents the material in the CPI phase affects the film's current-voltage charactersitics. Moreover, the conditions for the insulating state to subsist in InO may be disrupted by irradiation, through the decrease of the charging energy or the breaking of Cooper pairs.

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РАДИЈАЦИОНА ОТПОРНОСТ ФИЛМОВА ИНДИЈУМ-ОКСИДА У СТАЊУ ИЗОЛАТОРА СА КУПЕРОВИМ ПАРОВИМА

У раду се изучавају могући радијациони ефекти код филмова индијум-оксида у стању изолатора са Куперовим паровима. Ефекти зрачења предвиђају се на основу Монте Карло симулације. Резултати комбиноване теоријске и нумеричке анализе указују да промене у испитиваним филмовима изазване зрачењем могу значајно да утичу на њихове струјно-напонске карактеристике, као и да је могућ прелазак материјала у проводно стање, услед нарушавања грануларне структуре материјала. Раскидање Куперових парова, до кога долази у интеракцијама са упадним зрачењем и јонима узмаклим унутар InO_x филмова, такође може да разруши услове неопходне за опстајање овог специфичног изолаторског стања.

Кључне речи: индијум-оксид, изолатор са Куперовим паровима, радијациона оштећења, Монте Карло симулација