# EFFECTS OF ELECTRON IRRADIATION ON SUPERCONDUCTING PROPERTIES OF $Bi_2Sr_2CaCu_2O_8$/MgO SUPERCONDUCTOR COMPOSITE

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## ABSTRACT

*Among the challenges for superconducting devices to be applied in industry are the need for high transport critical current density ($J_c$) and sustainability of the device in different environment. For superconducting material to maintain high $J_c$, effective flux pinning centers are needed. The addition of small size MgO particles in bulk $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) superconductor has been proven to enhance the effective flux pinning centers in the superconducting material. Nevertheless, the flux pinning properties of the superconducting materials may change if they are exposed to radioactive environment. Electron irradiation is one of the common techniques that can be used to study the impact of irradiation on superconducting materials. In this work, a small amount of nanosize MgO particles were used as the flux pinning centers for Bi-2212 superconducting material. The Bi-2212/MgO composite was heat treated and followed by partial melting and slow cooling. Some of the samples were subjected to electron irradiation using the facility at the Malaysian Nuclear Agency. Characterizations of non-irradiated and irradiated samples were performed via X-ray Diffraction Patterns (XRD), Scanning Electron Microscopy (SEM) and measurements of $J_c$ dependence on temperature in self-field. Higher $J_c$ indicates better flux pinning properties in irradiated superconductor composite. This is achieved if defects with larger radius with dimension comparable to the coherence length of the superconducting material were created. On the other hand, decreased in $J_c$ indicates ineffective flux pinning and this is attributed to the overlapping of defects that break the superconducting region. Our study showed that electron irradiation deteriorated the flux pinning properties of the Bi-2212/MgO superconductor composite.*

## ABSTRAK

*Antara cabaran-cabaran itu kerana alat-alat keberaliran lampau untuk digunakan dalam industri ialah perlukan ketumpatan arus gentingpengangkutan yang tinggi (Jc) dan ketahanan peranti dalampersekitaran lain. Kerana bahan mengalir lampau mengekalkan Jctinggi, fluks berkesan meletakkan pusat-pusat diperlukan. Tambahansaiz kecil zarah-zarah MgO dalam pukal Bi2Sr2CaCu2O8 (Bi-2212)superkonduktor telah terbukti untuk meningkatkan fluks berkesanmeletakkan pusat-pusat dalam bahan mengalir lampau. Walaubagaimanapun , fluks meletakkan ciri-ciri bahan-bahan keberaliran lampau boleh berubah jika mereka ialah didedahkan kepada persekitaran radioaktif. Penyinaran elektron ialah satu daripadateknik-teknik umum yang boleh digunakan bagi mengkaji kesan penyinaran di bahan-bahan keberaliran lampau. Dalam tugas ini, sedikit zarah-zarah saiz-nano MgO telah digunakan apabila fluksmeletakkan pusat-pusat kerana bahan mengalir lampau Bi- 2212. Dwi 2212 / rencam MgO ada haba merawat dan diikuti oleh separapeleburan dan penyejukan yang perlahan. Beberapa contoh-contohbawah penyinaran elektron menggunakan kemudahan itu di Malaysian Nuclear Agency. Gambaran sifat tidak* *menerangi danmenerangi contoh-contoh telah diusahakan melalui X-ray Diffraction Patterns (XRD), Scanning Electron Microscopy (SEM) dan ukuran-ukuran pergantungan Jc di suhu di diri bidang. Jc lebih tinggimenunjukkan fluks lebih baik meletakkan ciri-ciri dalam menerangirencam superkonduktor. Ini mencapai jika kecacatan-kecacatandengan jejari lebih besar berdimensi setanding bagi panjang kekoherenan bahan mengalir lampau diwujudkan. Sebaliknya,mengurangkan dalam Jc menunjukkan fluks tidak berkesanmeletakkan dan ini ialah dianggap berpunca daripada bertindihberpaling tadah itu memecahkan rantau keberaliran lampau. Kajian menunjukkan kami penyinaran elektron itu rosak fluks meletakkanciri-ciri Bi- 2212 / rencam superkonduktor MgO.*

**Keywords:** Bi-2212 superconductor; flux pinning centers; electron irradiation; transport critical current density

## INTRODUCTION

Fabrication of superconducting material into wires and tapes with optimum superconducting properties is essential for the application of high-temperature superconducting material in various fields. In such applications, high transport current density ($J_c$) and sustainability of superconducting properties such as $J_c$ and transition temperature ($T_c$) in high magnetic fields are among the most important criteria. The $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) superconductor material is an outstanding candidate for consideration due to its phase stability, $T_c$ and excellent $J_c$ [1]. For the superconducting materials to be able to maintain high $J_c$ in magnetic field, they must have effective flux pinning centers. Although the weak-link problem has been partially solved in Bi-2212 superconductor by partial-melt processing, the limitation from flux pinning, which determines the intrinsic $J_c$, remains the most serious challenge for the practical application of Bi-2212 at elevated temperature and in extreme environment. However, sustainability of $J_c$ could be optimized with enhancement of flux pinning properties.

In previous studies on the effect of addition of small size MgO particles into Bi-2212 superconductor, the MgO particles were found to trap within the Bi-2212 superconducting grains as second-phase defects and enhanced the flux pinning in the Bi-2212 superconductor [2,3]. This indicates that defects are responsible in enhancing flux pinning properties and consequently the $J_c$. In another study, it was found that enhancement of $J_c$ in superconducting material could be established if radius of defect is comparable with the dimension of coherence length of the material [4]. Several other groups have been using neutron irradiation to introduce larger defects in superconducting material and consequently enhanced the flux pinning properties of the material [4-6]. According to Krutzler et al. [4] in their study on $MgB_2$ doped with carbon, the defect structure introduced by neutron irradiation provides a more efficient pinning structure than defects created by carbon doping. Zehetmayer et al. [5] in their study on Hg-based high temperature superconductor discovered that the effect of neutron irradiation is more pronounced at elevated temperature due to large defects created by the irradiation. Aoki et al. [6] in their work on the effect of neutron irradiation on superconducting tapes found that the superconducting characteristics of the tapes did not deteriorate under irradiation. Experimental results showed that dispersed local superconducting regions may be unified to form a continuous percolating network using neutron irradiation. Nevertheless, irradiation has the tendency to cause the superconductive volume fraction to be increased or decreased, and affect the $T_c$ value via Cu-O bond length [7]. In addition, the $J_c$ value was found to decrease under irradiation if the area occupied by columnar defects in $a$-$b$ plane decreases and consequently deteriorated the pinning force [8].

The aim of this work is to study the effect of electron irradiation on the flux pinning properties of the Bi-2212/MgO superconductor composite. In this study, some of the bulk samples of Bi-2212/MgO composite are subjected to electron irradiation. Eventually, both the non-irradiated and irradiated samples were characterized through X-ray Diffraction Patterns (XRD), Scanning Electron Microscopy (SEM) and measurements of $J_c$

dependence on temperature in self-field. Our study showed that the $J_c$ of Bi-2212/MgO superconductor composite decreased when subjected to electron irradiation and this indicates deterioration of the flux pinning properties.

## METHODOLOGY

Preparation of Bi-2212/MgO composite was performed using the conventional solid-state reaction method. Nanosize MgO particles with percentage weight of 3% was added to the Bi-2212 superconducting powder. The Bi-2212/MgO composite was subjected to partial melting and slow cooling process. High-purity $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) powder, product of Alfa, USA with an average size of 5 μm was used in preparation of the samples. The nanosize MgO powder was product of Aldrich, USA with an average grain size of 100 nm and purity of 99.998%.

The ALURTRON plant electron beam facility at the Malaysian Nuclear Agency (EPS 3000, Electron Processing System) was used to irradiate the samples. The electron beam processing facility comprising an electron beam machine (accelerator) provides fast irradiation processing with a high efficiency and high uniformity. The electrons generated are directed towards the target material to impart ionization, degradation, sterilization, irradiation, and radiation dose. Irradiation is controlled by regulating the irradiation time and achieved evenly over wide areas of materials at room temperature. The plant is equipped with electron beam machines with high-energy 1 MeV to 3 MeV and current with 0 to 30 mA. In this experiment irradiation was operated at 3 MeV, 10 mA and radiation dose of 200 KGray.

For characterization, structural investigation of non-irradiated and irradiated samples were conducted using X-ray Diffraction (XRD) to confirm their phase formation. Microstructure investigation was conducted using the Scanning Electron Microscopy (SEM). The cryogenic four-point probes refrigeration system used used to carry out the electrical resistance and transport critical current measurements.

### *Flux Pinning and Transport Current*

Figure 1 shows the flux tubes in type-II superconductors and in principle they are able to move freely and adjust their density according to the applied field. However, inhomogeneities in the superconductor due to grain boundaries and lattice defects creates an energy barrier that must be overcome in order to move the vortices. Due to this so-called flux-pinning, the magnetic flux in the superconductor will not change in a reversible manner as the externally applied field changes, and the work needed to overcome this pinning force is related with some losses in the superconductor. Flux-pinning is therefore the fundamental reason why superconductors of type-II exhibit hysteresis [9].

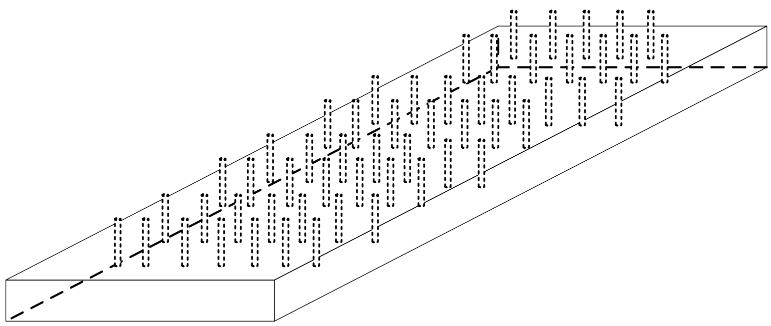


Figure 1: Flux passing through each tube of normal region, and a supercurrent shields the surrounding superconducting regions from the flux

The vortex region has the diameter of the coherence length ξ, which in a type-II superconductor is smaller than the penetration depth λ Furthermore, the flux tubes repel each other. This leads to the opening of superconducting path where supercurrent may pass through. A current that passes the flux lines produces a Lorenz-force $F_L = J \times \ _0$ upon each vortex. The vortices will, however, remain in their place as long as this Lorenz-force is inferior to the pinning force $F_p$. At some critical current density $J_c$, the Lorenz-force overcomes the pinning force and the vortices starts to move and the phenomena is known as flux-flow [10]. The critical current $I_c$ of a type-II superconductor is determined by multiplying $J_c$ with the cross-section through which the current flows. In practice, the critical current is often defined to be the current, at which an induced electric field reaches $10^{-4}$V/m. The vortices can also start to move because of a reduced pinning force that has its origin in thermal activation of the lattice and initiates flux creep.

## RESULTS AND ANALYSIS

The XRD patterns of the Bi-2212/MgO superconductor composite showed a well defined peaks, all of which could be indexed on the basis of a Bi-2212 phase structure as shown in Figure 2. The (002) peak, which is the characteristic of the Bi-2212 phase, can be observed clearly in both the non-irradiated and irradiated samples. A few unknown peaks were observed in the XRD patterns of the irradiated samples. The unknown peaks are likely due to the presence of oxide impurities resulted from electron irradiation [11]. Irradiation could caused damaging effect on the bonds in the *Cu-O* planes of the superconducting region and decreases the number of holes in the lattice [7].

The SEM micrographs in Figure 3 (a) and Figure 3 (b) show the microstructure of Bi-2212 phase of non-irradiated and irradiated. The size of the Bi-2212 platelets remains about the same in both samples with an average size of about 1 μm. Nevertheless, for the electron irradiated samples, the SEM microstructure shows higher porosity and the orientation of the grains is much more perpendicular to the *c*-axis. The *c*-axis orientation resulted in decreasing area of columnar defects in the *a*-*b* plane [8]. Consequently, the smaller columnar defects area deteriorates the $J_c$ of the irradiated sample.

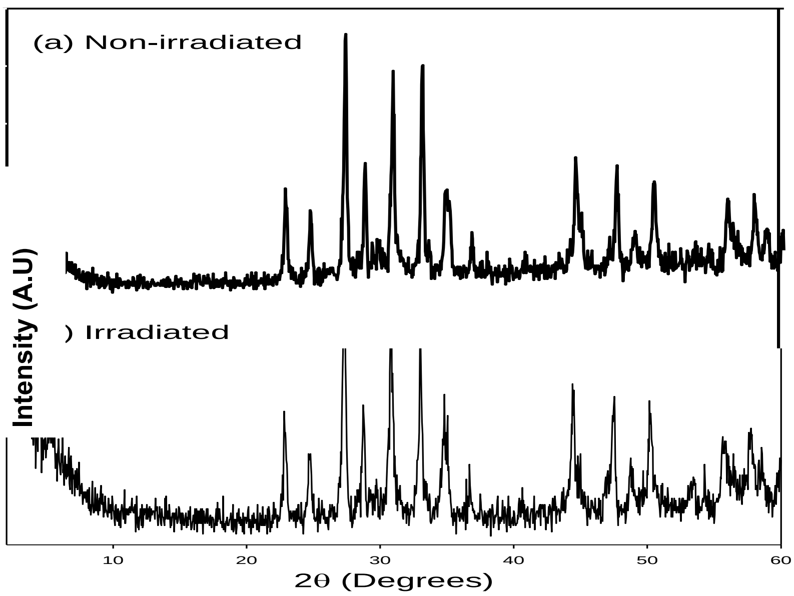
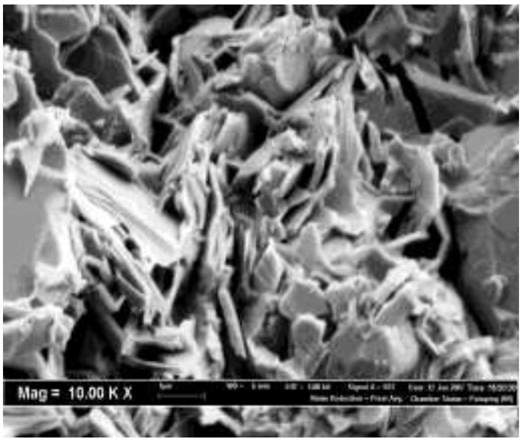
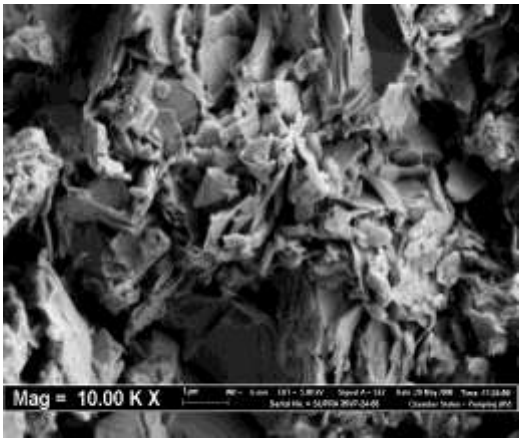



Figure 2: XRD patterns of (a) non-irradiated, and (b) irradiated Bi-2212/MgO superconductor composite




(a) (b)

Figure 3: SEM micrographs of (a) non-irradiated, and (b) irradiated Bi-2212/MgO superconductor composite

Table 1: $T_c$ and $J_c$ values of non-irradiated and irradiated Bi-2212/MgO superconductor composite

| Sample | $T_c$ (K) | $J_c$ (A/cm$^2$) at 20 K | $J_c$ (A/cm$^2$) at 30 K | $J_c$ (A/cm$^2$) at 40 K | $J_c$ (A/cm$^2$) at 50 K |
|---|---|---|---|---|---|
| Non-irradiated | 84 | 6.77 | 6.00 | 5.32 | 4.44 |
| Irradiated | 56 | 1.58 | 1.37 | 1.05 | 0.81 |

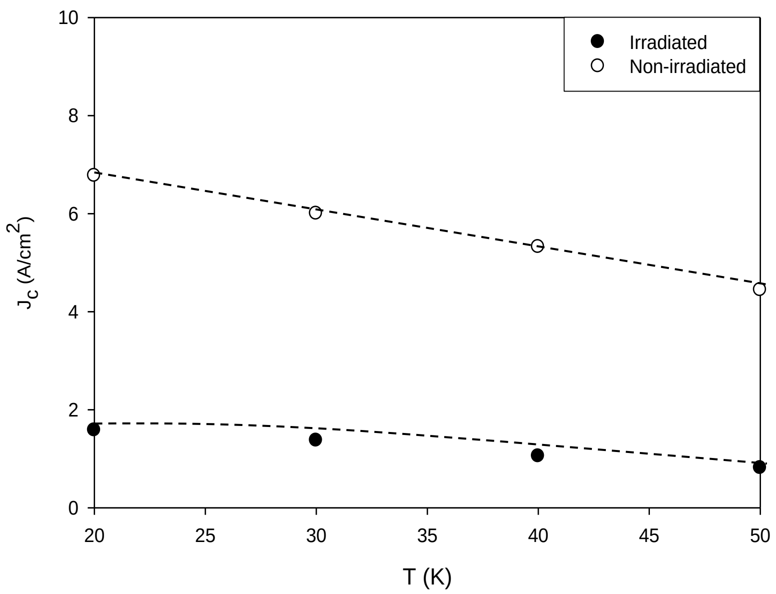



Figure 4: Temperature dependence of $J_c$ of of non-irradiated and irradiated Bi-2212/MgO superconductor composite. (The dotted lines are to guide the eye only).

Table 1 show the $T_c$ and $J_c$ values of non-irradiated and irradiated Bi-2212/MgO superconductor composite. The $T_c$ value of the irradiated sample decreased and this may be attributed to change in oxygen contents as described by Bódi et al. [7]. The presence on oxide impurities as shown in the XRD patterns promote weak-links along the grain boundaries of the superconducting region and contributed to the lower $J_c$ values in the irradiated sample.

Figure 4 shows the temperature dependence of $J_c$ in zero magnetic fields for the non-irradiated and irradiated samples. The $J_c$ decreased with increasing temperature as the consequence of thermal activated flux creep. Using a self-field approximation together with $J_c$ dependence on temperature [11, 12], we found that the characteristic length ($L_c$) associated with the pinning force is approximately the same as the average grains size ($R_g$) for non-irradiated sample. For the irradiated sample, it was found that $L_c > R_g$. The relationship between $L_c$ and $R_g$ is important since $J_c$ value depends on the average grain size of the samples, where $J_c$ is enhanced as the size of the grains decreased [12].

## CONCLUSION

In this study, electron irradiation was found to have detrimental effect on the superconducting properties of the Bi-2212/MgO superconducting composite. There are several factors that contributed to the degrading effects. The electron irradiation damaged the bonds in the *Cu-O* planes of the superconducting region and consequently, reduced the number of holes in the lattice structure of the composite. Decreasing area of columnar defects in the *a-b* plane contributed to the decrease in $J_c$ of the irradiated sample. Electron irradiation produced oxide impurities that promote weak-links along the grain boundaries of the superconducting region and resulted in lower $J_c$ values of the irradiated sample.

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