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# Effect of laser irradiation on the superconducting properties of high-$T_c$ $SmBa_2Cu_3O_x$

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**Abstract.** Studies of the effect of high power laser (Q-switched Ruby laser, 694 nm, 30 ns) irradiation on the critical current density ($J_c$) and magnetic hysteresis at 77 K and temperature variation of microwave induced d.c. voltage on $SmBa_2Cu_3O_x$ ceramic samples have been performed. Irradiation did not substantially change $T_c$ but caused a strong increase in $J_c$ and magnetic hysteresis at 77 K. The microwave-induced d.c. voltage at 77 K showed appreciable decrease after irradiation. SEM studies showed grain growth due to sintering which improves the interconnectivity among the superconducting grains. These are attributed to physical densification and consequent reduction in the number of weak links. The increase of magnetic hysteresis after laser irradiation is presumably connected with the creation of defects which act as pinning centres. Thermal modelling suggests that on irradiation the surface melts up to a depth of 1 $\mu$ and laser-induced evaporation occurs at energy density of 2·5 J/cm$^2$.

**Keywords.** Laser irradiation; critical current density; pinning centre; weak link.

## 1. Introduction

High-temperature superconducting oxides with high $J_c$ ($10^7$ A/cm$^2$) (Dinger *et al* 1987) are of current interest because of their potential applications in cryoelectronics, superconducting magnets, magnetic shields, and rf accelerator cavities. Study of the effect of microwave radiation on Josephson junctions has found a number of applications. It has also increased the fundamental understanding of weak-link phenomena in superconductivity (Senoussi *et al* 1988; McHenry *et al* 1988). Recently, it has been reported that the $J_c$ of rare-earth based barium cuprates can be increased by neutron (Wille *et al* 1988) and proton (Wisniewski *et al* 1988) irradiation. However gamma ray irradiation of $YBaCu_3O_{7-x}$ did not result in any changes of its superconducting properties (Bohandy *et al* 1987). On the other hand, reduction of $T_c$ with increasing neutron (Kupfer *et al* 1987; Cost *et al* 1988; Wille *et al* 1988), ion (Clark *et al* 1987), and electron (Stritzker *et al* 1988) irradiation has been reported of $YBa_2Cu_3O_{7-x}$. The effect of laser irradiation on various properties of high-$T_c$ superconductors has not been reported so far. This paper presents the effect of pulsed laser radiation on $J_c$, magnetization and microwave-induced d.c. voltage (inverse a.c. Josephson effect) in $SmBa_2Cu_3O_{7-x}$ (SBCO) superconductor which is correlated with microstructural studies.

## 2. Experimental

The superconducting $SmBa_2Cu_3O_{7-x}$ samples were prepared by standard solid-state reaction process. Stoichiometric quantities of AR-grade $Sm_2O_3$, $Ba(NO_3)_2$, and

$Cu(NO_3)_2 \cdot 3H_2O$ were mixed thoroughly and heated at 900°C with several intermediate grindings. The fine powders were then pelletized (4 tons/cm$^2$) and sintered at 960°C in $O_2$ atmosphere and slowly cooled to 200°C. The samples were cut into rectangular shape ($1\cdot5 \times 1\cdot5 \times 8\,mm^3$) for electrical measurements. Standard four-probe technique was used for the measurement of $T_c$ and $J_c$. Connections were taken by copper wires soldered with indium onto the predeposited thick silver contact pads. Samples were irradiated in air using a Q-switched Ruby laser (694 nm, 30 ns, $E = 2\cdot5\,J/cm^2$, spot diameter 8 mm) keeping the samples 60 cm away from the laser window. Low-field magnetization was measured on PAR-vibrating sample magnetometer (model 150 A) with a sensitivity of $10^{-4}$ emu. The cylindrical samples were oriented with their long axis parallel to the applied magnetic field to minimize the demagnetization effect and zero field cooled to 77 K. For study of the inverse a.c. Josephson effect (Rao *et al* 1989) samples were mounted inside an X-band wave guide and irradiated with highly stabilized phase-locked microwave radiation (at 9·67 GHz). The d.c. voltage was measured using a high impedance nanovoltmeter. Correction for thermal emf was applied to each measurement.

## 3. Results and discussion

$J_c$ as a function of transverse applied magnetic field at 77 K is presented in figure 1 for both unirradiated and irradiated SBCO superconductor. It is observed that on irradiation, critical temperature ($T_c$) did not change much. However, $J_c$ increases appreciably after laser irradiation at 77 K. $J_c$ decreased sharply with the increase of magnetic field, but a weaker dependence was observed at higher fields. This rapid fall of $J_c$ may be understood by considering that the sample consists of a large number of weakly-coupled superconducting grains. It is interesting to note that the magnetic field dependence of $J_c$ in the irradiated sample was weaker than that of the unirradiated one.

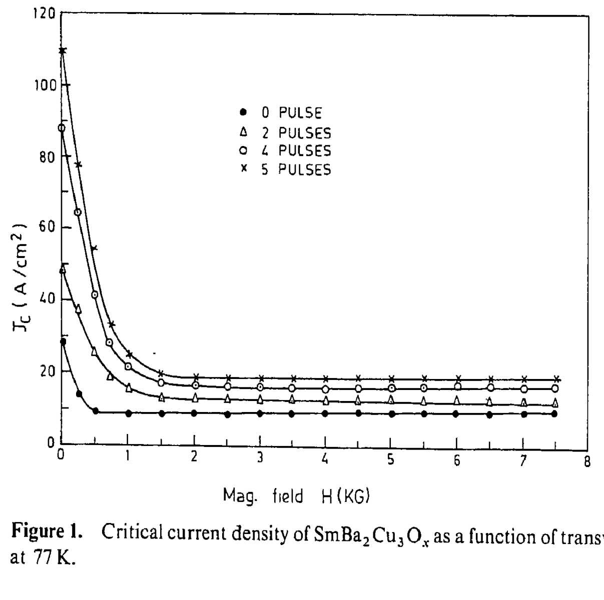


**Figure 1.** Critical current density of $SmBa_2Cu_3O_x$ as a function of transverse magnetic field at 77 K.

This enhancement of $J_c$ at higher magnetic fields is presumably due to the creation of additional defects by laser irradiation which act as pinning centres. Hence larger transport current is required to move the additional pinned vortices.

Low-field magnetization measurements at 77 K before and after laser irradiation on SBCO sample are presented in figure 2. It is observed that flux expulsion decreased with increasing laser irradiation, but magnetic hysteresis increased. This may be due to the creation of defects produced by irradiation. These additional aefects act as pinning centres which pin a larger number of normal cores. This reduces the superconducting

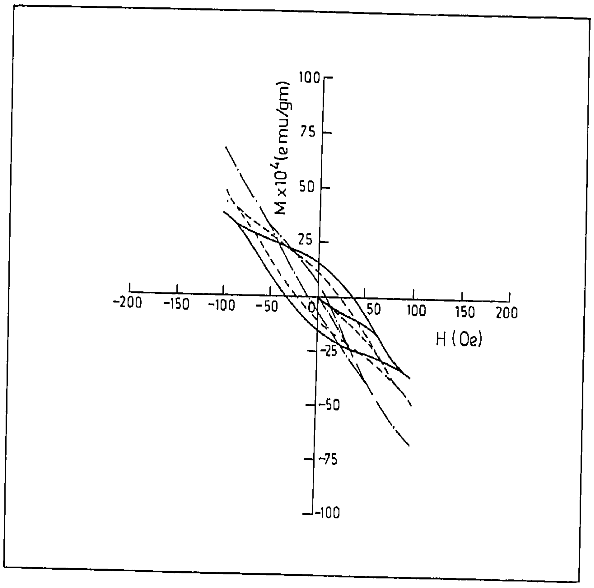


**Figure 2.** Magnetization vs applied magnetic field of $SmBa_2Cu_3O_x$ for different laser pulses (–·– unirradiated, ----- 3 laser pulses, ——— 5 laser pulses).

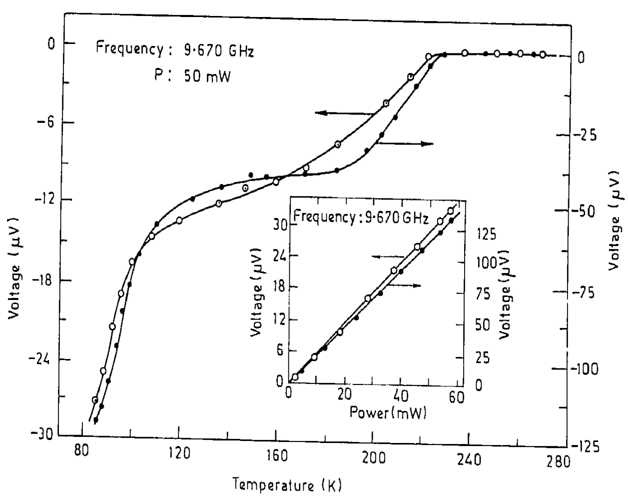


**Figure 3.** Temperature dependence of microwave-induced d.c. voltage for irradiated (⊙5 pulse) and unirradiated ( ) $SmBa_2Cu_3O_x$. Inset shows the power dependence of d.c. voltage at 77 K.

volume fraction resulting in a lower flux expulsion. Further, the flux trapped at these defect sites create additional hysteresis.

Figure 3 shows the variation of microwave-induced d.c. voltage as a function of temperature for both irradiated and unirradiated samples at a fixed power level (50 mW) at 9·670 GHz. The inset of figure 3 shows the variation of induced voltage as a function of microwave power at 77 K for both unirradiated and irradiated samples. It is

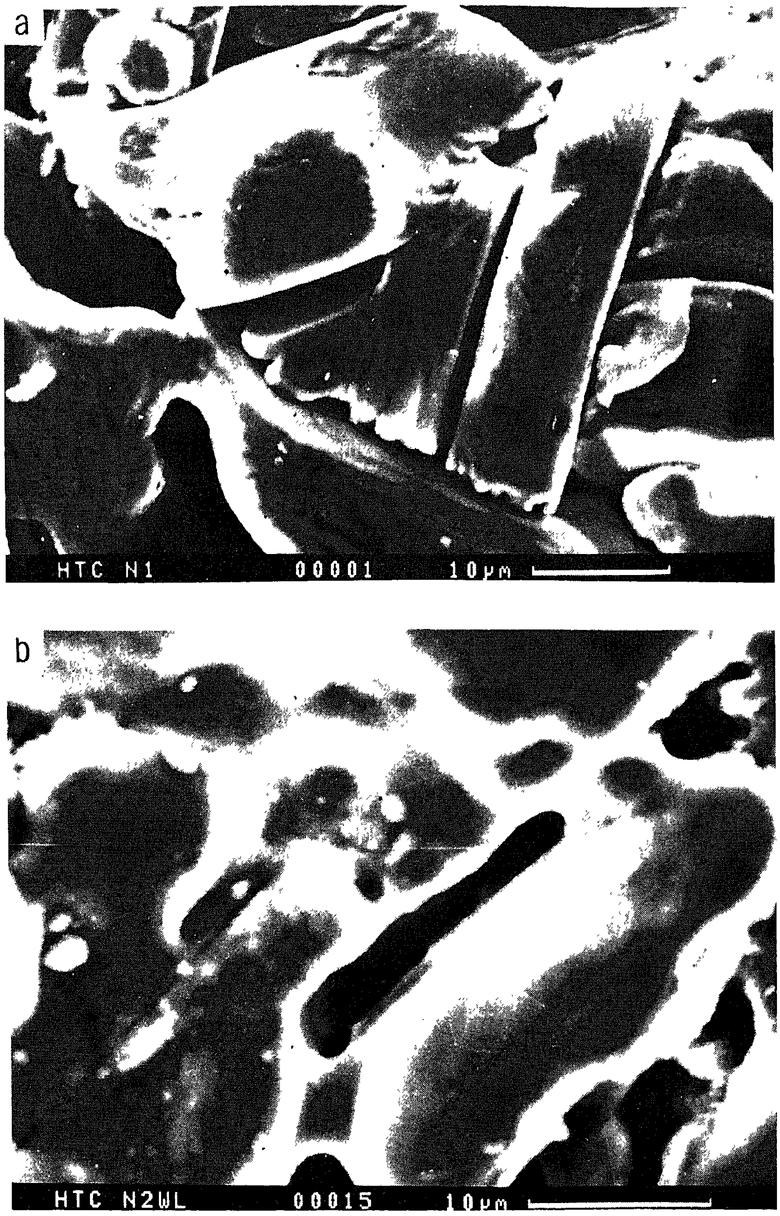


**Figure 4.** Scanning electron micrographs of $SmBa_2Cu_3O_x$ before (**a**) and after (**b**) irradiation.

observed that the microwave-induced d.c. voltage for the irradiated samples decreased with increasing number of laser pulses. This is because of the reduction in the number of weak links between the superconducting grains.

Typical scanning electron micrographs of SBCO samples before and after laser irradiation are presented in figure 4. These studies showed grain growth due to sintering and interdiffusion of the grain boundaries which seemed to improve the interconnectivity among the superconducting grains after irradiation.

Thermal modelling (figure 5) of laser heating on surface layers of samples was carried out by solving the time-dependent heat flow equation

$$C\rho(\mathrm{d}T/\mathrm{d}t) = \mathrm{d}/\mathrm{d}x(K\,\mathrm{d}T/\mathrm{d}x) + Q(x,t), \tag{1}$$

where $C$ = heat capacity = 0·0336J/g − K; $\rho$ = density = 6·0 g/cm$^3$; $K$ = conductivity = 0·03 watt cm$^{-1}$ K$^{-1}$ and $Q$ = laser intensity = 83 MW/cm$^2$. The equation solved by finite difference method showed (figure 5) that the total power was absorbed within only 1·5 $\mu$m depth. The depth of melting was estimated to be 8000 Å (assuming a melting point of 1400 K). It is observed that laser-induced evaporation also occurs at these energy densities (2·5 J/cm$^2$). The large thermal gradients act like thermal spikes on the sample surface for a very short time. These thermal spikes increase the defect density and caused inhomogenous distribution of defect concentration. These act as pinning centres and help to increase $J_c$. The interdiffusion of grains due to the large thermal gradients facilitates the reduction of total number of grain boundaries and hence the number of weak links. This is further confirmed by the decrease in the microwave-induced d.c. voltage after irradiation. The enhancement of $J_c$ and decrease in microwave-induced d.c. voltage after irradiation may thus be attributed to physical densification and consequent reduction in the total number of weak links.

In conclusion, it was found that a single laser pulse did not change $T_c$. However, irradiation with a large number of pulses resulted in a decrease of $T_c$. A substantial decrease in the low-field magnetization, microwave-induced d.c. voltage and increase in $J_c$ were observed due to physical densification and consequent reduction in the total number of weak links after laser irradiation. Microstructural differences seen from SEM studies after irradiation showed grain growth due to laser-induced sintering which improved the interconnectivity among the superconducting grains. Thermal modelling of laser heating suggests that the surface temperature exceeds 1500°C for a duration of 10 ns at $E$ = 2·5 J/cm$^2$ and melting occurs up to a depth of a micron. Laser-induced evaporation also occurs at such energy densities.

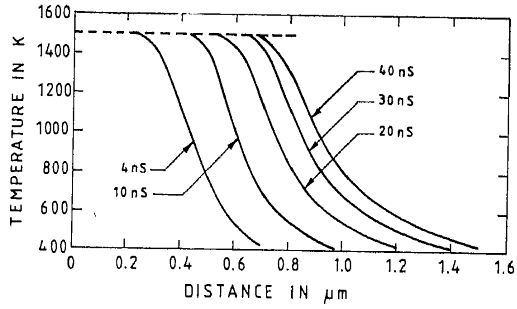


**Figure 5.** Temperature vs heating depth at different times for laser heating of $SmBa_2Cu_3O_x$ from thermal modelling.

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