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DIODE CHARACTERISTICS OF $\text{YBa}_2\text{Cu}_3\text{O}_7/n$ -TYPE SILICON CONTACTS

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The text of the above article should be the following:

The temperature dependences of diode characteristics were measured on high- T_c -superconducting $\text{YBa}_2\text{Cu}_3\text{O}_7$ (polycrystalline)/ n -type silicon (monocrystalline) contacts using a common two-pole-technique at low frequencies. The non-superconducting p -type semiconductor $\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$ (polycrystalline) served as a reference substance. The temperature coefficients of the diffusion voltage, the diffusion current, and the saturation current were found to be finite at $T > T_c$, but almost zero at $T \leq T_c$. At $T = 78$ K, the diffusion voltage of the diode $\text{YBa}_2\text{Cu}_3\text{O}_7/n$ -type silicon was about 200 mV lower compared to that of the reference diode $\text{YBa}_2\text{Cu}_3\text{O}_{6.5}/n$ -type silicon.

The observed phenomena are explained in terms of different charge carrier behavior in the superconducting ceramics above and below T_c .

1. Introduction

The conduction mechanism of high- T_c -superconductors is still not well understood.¹⁻⁷ Investigations on the charge carrier transfer across the interface between the p -type semi- or superconducting ceramics and a n -type semiconductor in dependence on the temperature should provide new information on the conduction mechanism.

In this paper, measurements of the diode characteristics depending on the temperature are reported using contacts between the superconducting ceramics $\text{YBa}_2\text{Cu}_3\text{O}_7$ or the non-superconducting ceramics $\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$ and n -type silicon single crystals denoted as diodes I and II, respectively. A change in the conduction mechanism of the diodes should be reflected in the diode characteristics above and below the critical temperature T_c .

2. Experimental

The superconducting ceramics $\text{YBa}_2\text{Cu}_3\text{O}_7$ with $T_c = 92$ K and the non-superconducting ceramics $\text{YBa}_2\text{Cu}_3\text{O}_{6.5}$ were prepared from the oxides by sinter-pressing and annealing under oxygen atmosphere in the usual way.⁸⁻¹⁰ The

samples of about 14 mm diameter and 4 mm thickness were mechanically polished and thoroughly cleaned with acetone. Low ohmic electrical contacts were performed with silver conducting epoxy resin or paint.

The *n*-type semiconductor were (111) silicon single crystal discs of about 17 mm diameter and 1 mm thickness doped with phosphorus exhibiting a donor density of $N_D \approx 8 \times 10^{13} \text{ cm}^{-3}$ corresponding to a specific resistivity of $\rho \approx 55 \Omega\text{cm}$. After etching with hydrofluoric acid, one side of the samples was nickel plated and copper leads were soldered on the nickel surface as low ohmic electrical contacts.

To form a diode, the ceramics and a silicon single crystal disc were mechanically pressed together. The diode characteristics¹¹⁻¹³ depending on temperature were measured using a cryostate (Cryophysics, model LTS-22-DRC 91 C) under vacuum conditions.

3. Results and Discussion

Figure 1 shows the diode characteristics of the superconducting diode I and the reference diode II at $T = 78 \text{ K}$. It is seen that the diffusion-voltage, U_d , of diode I is about 200 mV lower than that of diode II. Obviously, this must be correlated with different electronic properties of the superconducting and non-superconducting ceramics at liquid nitrogen temperature. The depletion layer width varies as the square root of the total electrostatic potential difference across the junction. For a transition of $\text{YBa}_2\text{Cu}_3\text{O}_7$ from a *p*-type semiconducting state to a superconducting state at $T = T_c$, the depletion layer width of the junction decreases which corresponds to a decrease of U_d .

Figures 2 and 3 show the temperature dependences of the diffusion-voltage and the diffusion current, $I_d = I(U_d)$, respectively. As expected, the diffusion-voltage

Fig. 1. Diode characteristics of diode I ($\text{YBa}_2\text{Cu}_3\text{O}_7/n\text{-Si}$) and diode II ($\text{YBa}_2\text{Cu}_3\text{O}_{6.5}/n\text{-Si}$) at $T = 78 \text{ K}$.

Fig. 2. Temperature dependence of the diffusion voltage, U_d , of diode I.

Fig. 3. Temperature dependence of the diffusion current, I_d , of diode I.

increases linearly and the diffusion-current decreases exponentially with decreasing temperature at $T > T_c$. The slope of the U_d versus T plot depends on the doping level of $n\text{-Si}$ and increases with decreasing donor concentration (Table 1). Surprisingly, both U_d and I_d become nearly constant at $T < T_c$. This effect may be explained by assuming a higher tunnelling probability due to the above-mentioned decrease of the depletion layer width at $T = T_c$.

Arrhenius plots of the diffusion current and the saturation current, I_s , are

Fig. 4. Arrhenius plots of the diffusion current, I_d , and the saturation current, I_s .

represented in Fig. 4. I_s was determined at a reverse bias of 1 V. A formal activation energy of $E_a = 0.028$ eV can be evaluated from the temperature dependence of I_d . Since I_d partly consists of diffusion and recombination-generation current contributions, which are both strongly dependent on the temperature, the activation energy E_a cannot be referred to a single process.

Due to the high carrier density in the superconducting ceramics, it was attempted to compare the hetero diode I with a homo one-sided $p^+ - n$ junction in order to determine the bandgap energy of n -Si,¹¹ which is known to be 1.1 eV

$$I_s \propto \exp\left(-\frac{E_g}{kT}\right). \quad (1)$$

From the slope of the Arrhenius plot of I_s in Fig. 4, a bandgap energy $E_g = 0.085$ eV was determined, which is by more than one order of magnitude too small, indicating that the $p^+ - n$ approach is obviously not valid in our case. However, it is interesting to note that I_s also seems to become temperature-independent at $T < T_c$.

In general, the forward characteristics of a homo p - n junction (e.g. silicon, or gallium arsenide) can be represented at room temperature empirically by¹¹

$$I_f \propto \exp\left(\frac{e \cdot U}{\eta kT}\right), \quad (2)$$

where e is the elementary charge and η denotes the ideality factor. At low current levels, recombination current dominates yielding $\eta = 2$ in a semilogarithmic plot, while at higher current levels, diffusion current prevails with $\eta = 1$. At even

Table 1. Temperature dependence of the diffusion voltage U_d as a function of the doping level (resistivity).

$dU_d/dT(\text{V deg}^{-1})$	n -Si resistivity(Ωcm)
-4.7 E-3	7500
-1.1 E-3	55

Table 2. Temperature dependence of the ideality factor η .

T/K	η
293	1.82
250	2.50
200	3.75
150	4.01
100	6.81
90	7.17
72	6.39

higher current levels, the current departs from $\eta = 1$ and increases more gradually with forward voltage. This behavior is associated with two effects: series resistance or high injection. In the latter case, the forward current is roughly expressed by¹¹

$$I_f \propto \exp\left(\frac{e \cdot U}{2kT}\right). \quad (3)$$

In the former case (series resistance), the IR drop reduces the bias across the depletion layer and

$$I_f \approx I_s \exp\left[\frac{e(U - I_f R)}{kT}\right]. \quad (4)$$

Although the hetero junction under investigation with a large misfit in the lattice parameter is not expected to fulfil the ideal diode characteristics, it is of interest to use the ideality factor and its temperature dependence in order to characterize the new junction. From Table 2, it can be seen that at room temperature, the η value is at least of the same order as known for the Si or GaAs p - n junctions. However, at lower temperatures, η departs more and more from ideality to higher values, pointing on series resistance limitation of the forward current. This is not surprising since the resistance of the semiconductor increases with decreasing temperature.

4. Conclusions

The general course of the diode characteristics and the right order of the ideality factor at room temperature confirm a typical diode action of the junction under investigation. The most interesting result of these investigations is the temperature independence of the characteristic diode parameters: diffusion voltage, diffusion current and saturation current at temperatures below T_c . This behavior indicates a predominating tunnelling process of charge carriers across the superconductor/ n -type semiconductor junction.

Such types of junctions could be applied to form superconducting diodes or transistors for cryogenic circuits. Due to the low diffusion voltage, low power dissipation and high speed switching can be achieved at cryogenic temperatures. These properties should allow to improve high density integrated circuits.^{14,15}

Acknowledgment

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