ELECTRIC FIELD EFFECT IN SUPERCONDUCTOR-FERROELECTRIC STRUCTURES

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Electric field effect (the E-effect) in superconductors has been studied since 1960 when Glover and Sherill [1] published their results on a shift of the critical temperature Tc about 0.1mK in Sn and In thin films under the action of the field E=300 kV/cm.
Stadler [2] was the first to study the effect of spontaneous polarization of ferroelectric substrate on the electric properties of superconductors.He observed that the reversal of polarization of TGS substrate under action of external electric field in Sn-TGS structures induced the Tc shift in Sn about 1.3 mK. Since in this case the effect is determined not by the electric field but by the spontaneous polarization,we may call this effect the P-effect.
High-Tc superconductors opened the new possibilities to study the E- and P-effects due to low charge carrier density,as compared to conventional superconductors,and to anomalously small coherence length.Experiments in this field began in many laboratories (see Refs.3 and 4 and the references cited therein) but a breakthrough was made in Ref.5 where a shift in Tc by 50 mK was observed in YBCO thin films.Much higher effects were observed in subsequent studies [3,4].The first experiments on the P-effect in high-Tc superconductors were reported in Refs.6,7.
In this report we shall give a short description of study on the P-effect in high-Tc superconductors.
In Fig.1 a typical structure for study of the P-effect is shown.
There is a number of advantages of the P-effect as compared to the E-effect [7],in particular,the surface charge density due to the spontaneous polarization in ferroelectrics can be significantly larger than the charge density induced by the electric field in ordinary dielectrics.In the case of superconductor-dielectric structure with capacitance C the density of surface charge induced by the gate voltage Vg is given by

$$Q^{(E)} = CV_G = \varepsilon_d V_G / 4\pi l_d = \varepsilon_d E / 4\pi \qquad (1)$$

and the change of the sheet density of charge carriers is

$$\Delta n_{sh}^{(E)} = Q^{(E)}/e = \varepsilon_d E / 4\pi e \qquad (2)$$

Here ε_d and l_d are dielectric constant and thickness of dielectric layer,respectively.
In the case of ferroelectric layer with polarization P one has

$$Q^{(P)} = P \ , \ \Delta n_{sh}^{(P)} = P/e \qquad (3)$$

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One can rewrite Eqs.2 and 3 in the more convenient form

$$\Delta n_{sh}^{(E)} = 5.5 \ 10^5 \ \varepsilon_d E \qquad (2a)$$
$$\Delta n_{sh}^{(P)} = 6.2 \ 10^{18} \ P \qquad (3a)$$

where Δn_{sh} is in cm^{-2}, E is in V/cm and P is in C/cm^2.

For the ratio of carriers sheet density cange in the P- and E-effects we have

$$\Delta n_{sh}^{(P)}/\Delta n_{sh}^{(E)} = 4\pi P/\varepsilon_d E = 1.1 \ 10^{13} \ (P/\varepsilon_d E) \qquad (4)$$

If we take the spontaneous polarization for ferroelectric perovskite $P = 10^{-4}$ C/cm^2 (which seems to be the maximum experimentally observed value) and suppose that dielectric layer has dielectric constant $\varepsilon_d = 100$, then the E-effect will be equal to the P-effect only in the electric field $E = 1.1 \ 10^7$ V/cm.This value is far beyond the breakdown field values for dielectric layers.

The other characteristic,very important in the study of the E-and P-effects,is the Thomas-Fermi screening length which describes the screening of the electric field or polarization by charge carriers in metals or degenerate semiconductors.The screening length is given by

$$l_{T.F.} = (\varepsilon E_F/6\pi n e^2 \ )^{1/2} \qquad (5)$$

or

$$l_{T.F.} = 6.1 \ 10^2 \ (\varepsilon E_F/n)^{1/2} \qquad (5a)$$

where ε is the dielectric constant of a superconductor,E_F is the Fermi energy,and n is the volume carrier density.In Eq.5a $l_{T.F.}$ is in cm, E_F is in eV, and n is in cm^{-3}.

For YBCO using Eq.5a and the appropriate values of parameters we have as an upper limit $l_{T.F.} = 1$ nm.

The change of sheet density in a superconductor under action of electric field or polarization is distributed along this length and for the total relative change of volume carrier density in the superconductor thin film of thickness $l_{T.F.}$ we have

$$\Delta n/n = \Delta n_{sh}/l_{T.F.} n \qquad (6)$$

For the film thickness l_s larger than $l_{T.F.}$ the change of sheet density should be referred to the thickness l_s.If the film resistance is completely determined by the carrier density then one obtains

$$\Delta R/R = \Delta n_{sh}/l_s n \qquad (7)$$

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If we take l_s= 100 nm , n= 4 10^{21} cm^{-3} and P= 7 10^{-5} C/cm^2 then we have $\Delta R/R$= 10^{-2} ,that is the switching of polarization in a ferroelectric from +P to -P should give the change in resistance in an adjacent superconductor film about 2% .If the critical temperature Tc of the superconductor is also proportional to the carrier density,then one should observe the Tc shift also by 2% .

The change of charge carrier density should also influence the resistance of superconductor in the mixed state though the mechanism of this effect may be different as compared to the normal state.

In Fig.2a the resistance change in the mixed state of YBCO film with thickness l_s 200 nm is shown as a function of electric field applied to BaTiO3 substrate.Fig.2b shows the polarization hysteresis loop in the same substrate at the same temperature.The YBCO film is deposited on (001) plane of BaTiO3,the thickness of the substrate is about 0.5 mm.From Fig.2 it follows that there is a distinct correlation between the resistance and polarization changes. The Tc shift in the same structure determined from temperature dependence of resistance is 0.5 K or 0.5 % which is near to the estimation from Eq.7.

In Fig.3 the resistance temperature dependences of YBCO films deposited on $LiNbO_3$ substrate are shown.The spontaneous polarization of LiNbO3 is 7 10^{-5} C/cm^2 , however the polarization in this crystal cannot be reversed at low temperatures due to very high coercive field.Therefore to observe the P-effect YBCO films were deposited on the opposite sides (+P and -P) of two single-domain LiNbO3 plates in one experiment in the identical conditions.One can see that there is a considerable shift of the Tc at R =0 by about 40 K.This shift is much larger than predicted by Eq.7 for the film with thickness about 100 nm.

For the possible application it is important to study the P-effect in superconductor-ferroelectric layered structure where both superconductor and ferroelectric are deposited as thin films.An example of such a structure is shown in Fig.4 [8].YBCO film 400 nm thick is deposited on NdGaO3 by laser ablation method.Onto the YBCO film BaSrTiO3 film with thickness 1500 nm is deposited by rf magnetron sputtering technique.Using BaSrTiO3 solid solutions gives the possibility to change the ferroelectric Curie temperature which can vary from liquid Helium region up to 400 K.This possibility may be useful to optimize the conditions for the E- and P-effects.Some characteristics of YBCO-BST structure are presented in Fig.5.

Along with the true E- and P-effects the elastic strain effect (the S-effect) should also exist.Indeed,under the action of electric field we have electrostrictive (any solids) and piezoelectric (crystals without inversion symmetry) strains in dielectric (ferroelectric) layers and there will be consequently elastic strains in superconductor film.These strains can change the superconductor electric properties.It was shown [9] that the elastic strains in BaSrTiO3 ceramic substrates resulted in the shift of the superconductor critical temperature Tc by 0.03 K in the electric field about 10 kV/cm.

The experimental results on the P-effect presented in Figs.2 and

3 have been obtained for YBCO films with thickness about 100 nm that is much larger than the Thomas-Fermi screening length.To increase the P-effect it is necessary to use ultrathin YBCO films comparable to the Thomas-Fermi screening length [10].Let us estimate the value of polarization of a ferroelectric layer which could switch ultrathin YBCO film from the N-state to the S-state,and vice versa,due to the P-effect.We shall discuss three-layered structure shown in Fig.6. Using Eqs.3 and 7 and assuming that $\Delta R/R = 1$ we have

$$P \ (C/cm^2) = (l_s n/6.2) \ 10^{-18} \ , \text{where } l_s \text{ is in cm and n is in } cm^{-3}.$$

Then for $l_s = 2.5$ nm and $n = 5 \ 10^{21} cm^{-3}$ one obtains $P = 2 \ 10^{-4} C/cm^2$. This value sould be divided over 4 due to the P reversal from $+P$ to $-P$ and due to the double ferroelectric layers in Fig.6. So, finally we have $P = 5 \ 10^{-5} \ C/cm^2$,more or less ordinary value for a number of ''strong'' ferroelectric crystals.

Another approach to this problem may also be used.If we assume that the resistance of the ultrathin film is of the order of the quantum unit $R_q = h/4e^2 = 6.45$ kΩ [11],and the change of the resistance under action of polarization,for transition from the N-state to the S-state,has the same value,then we obtain $P = 1/\mu R_q = 4e^2/\mu h$ or $P \ (C/cm^2) = 1.55 \ 10^{-4}/\mu$,where μ is mobility in cm^2/V s. For the mobility of the order of 1 cm^2/V s the polarization P has the same value as in the first estimation.

Thus,for ultrathin superconductor film it is possible to switch the film from the N-state to S-state by switching the polarization in ferroelectric layers under action of the electric field (Fig.6).

It should be noted that ferroelectric layers in superconductor-ferroelectric structures may have ferroelectric domain structure which can be used to form some weak links and N-S junctions in adjacent superconductor layers [12].

The P-effect in superconductors,as well as the E-effect,can in principle find many technical applications [4] :superconducting field effect transistors (SuFET),electrocryotrons,mixers,adjustable filters,etc.The advantage of the P-effect is the possibility to have devices with long-term memory.

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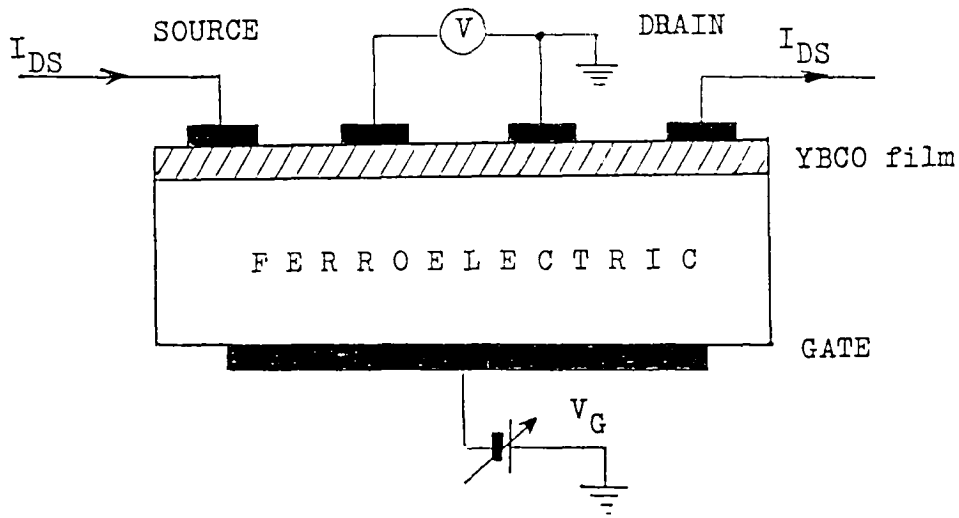
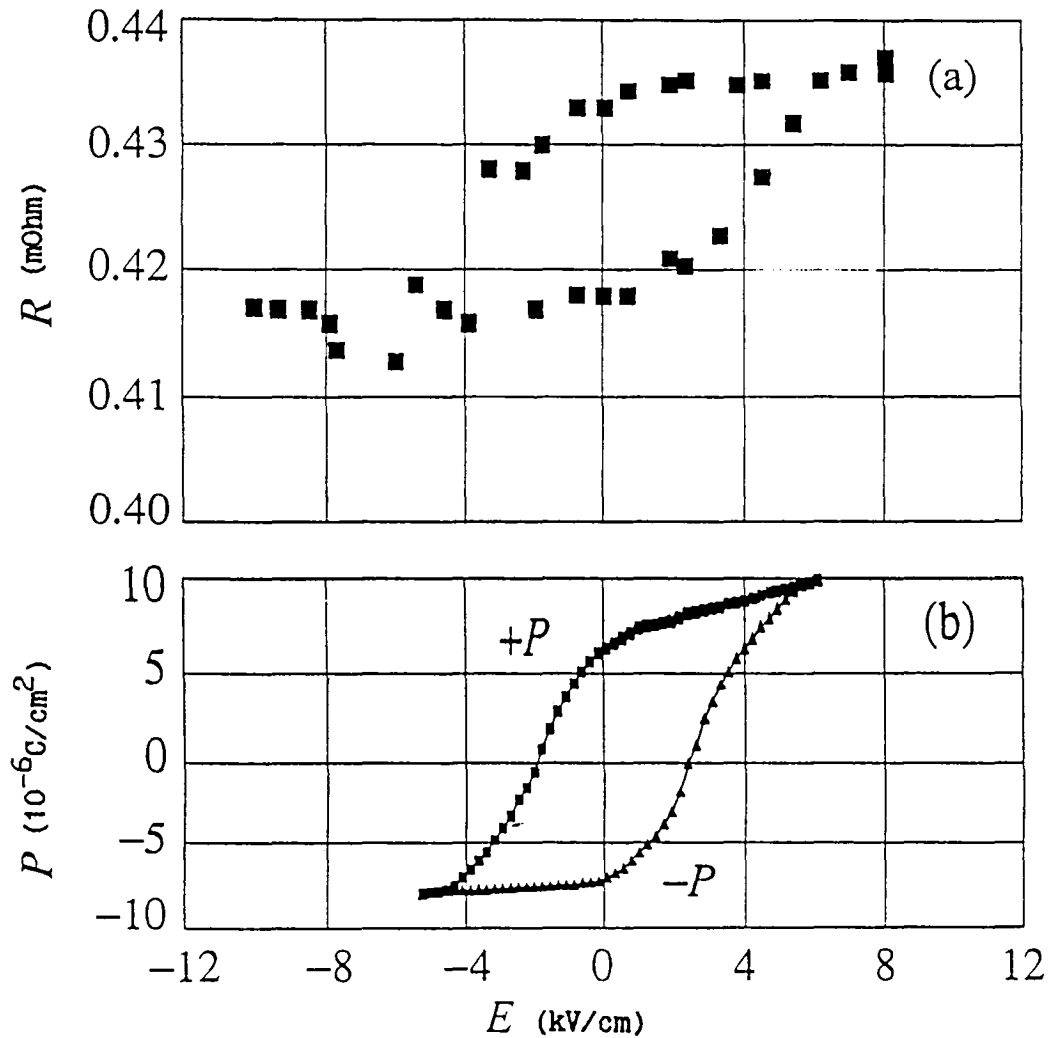Figure 1.- Typical structure for study of the P-effect.

Figure 2.- Resistance change in the mixed state of YBCO film on BaTiO3 substrate (a)
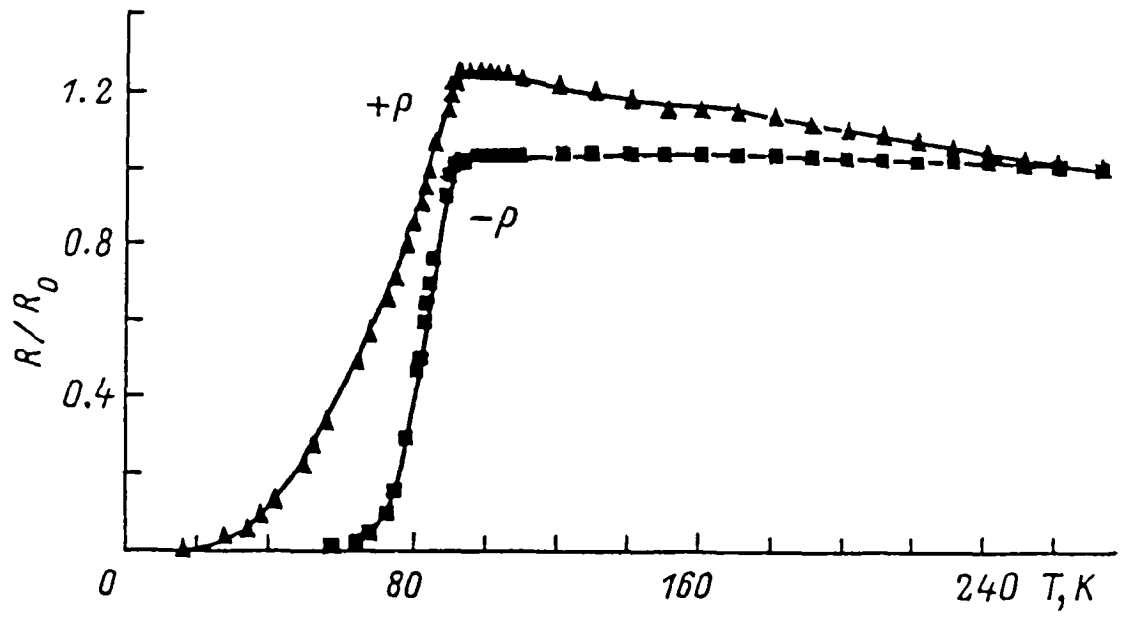and polarization hysteresis loop for the substrate (b) at 77 K.

Figure 3.- Temperature dependence of resistance of YBCO films deposited on the opposite sides (+P and -P) of LiNbO3 substrates (+P :polarization directed toward the film, -P :polarization directed away from the film).
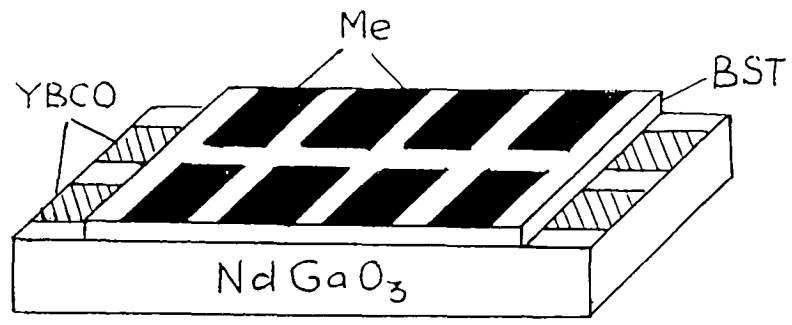

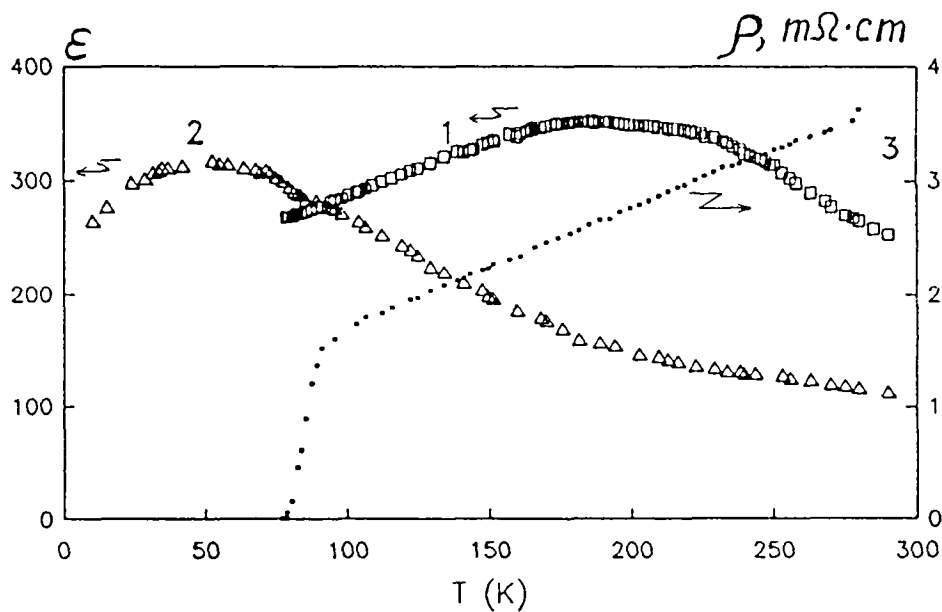Figure 4.- YBCO-BasrTiO3 (BST) - Metal structure.

Figure 5.- Temperature dependencies of the dielectric constant of $Ba_xSr_{1-x}TiO_3$ films with x-0.5 (1) and x=0.21 (2) and the resistivity of YBCO film (3) in the YBCO/BST/Au structure shown in Figure 4. The X values refer to the target.
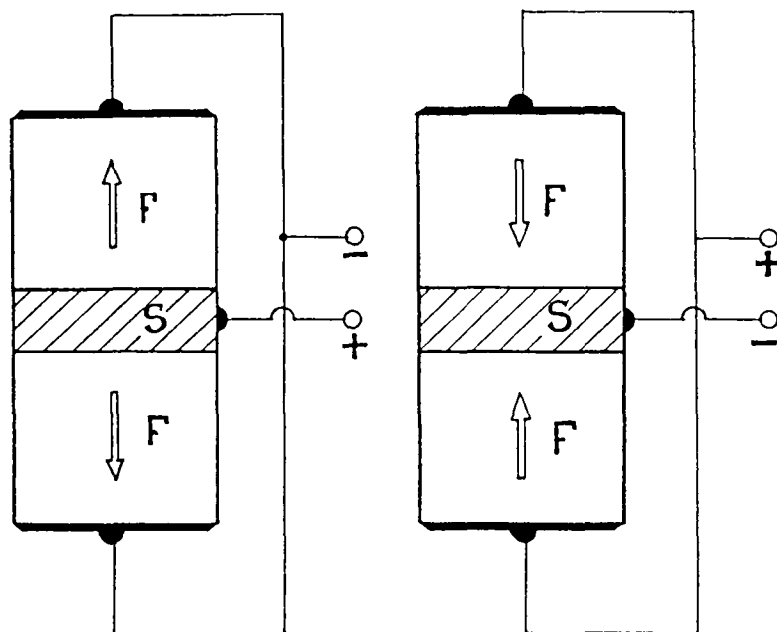

Figure 6.- Superconductor(S)-Ferroelectric (F) three-layered structure. The switching of polarization of the ferroelectric layers from the -P state to the +P state may induce transition of the superconductor layer from the S-state to the N-state.