Ginzburg–Landau theory of Josephson field effect transistors

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A theoretical model of high-T_c Josephson field effect transistors (JoFETs) based on a Ginzburg–Landau free energy expression whose parameters are field- and spatially-dependent is developed. This model is used to explain experimental data on JoFETs made by the hole-overdoped Ca-SBCO bicrystal junctions (three terminal devices). The measurements showed a large modulation of the critical current as a function of the applied voltage due to charge modulation in the bicrystal junction. The experimental data agree with the solutions of the theoretical model. This provides an explanation of the large field effect, based on the strong suppression of the carrier density near the grain boundary junction in the absence of applied field, and the subsequent modulation of the density by the field. © *1996 American Institute of Physics.* [S0003-6951(96)00542-6]

The development of practical high-T_c three terminal devices has received much attention recently. There are many different directions that have been investigated: the electric field effect transistor, the flux-flow transistor, quasiparticle injection devices, etc. The superconducting field effect transistors (suFETs) with a homogeneous thin film channel[1,2] and JoFETs with a Josephson junction channel[3–8] are electric field related devices. In general, the required electric field for the field effect in JoFETs is orders of magnitude smaller than the field required in suFETs with homogeneous thin film.

A basic question that therefore arises is to understand the large effect that an electric field has on the transport properties in JoFETs. Dong *et al.*[3,4] showed that there is a 23% modulation of the critical current on a grain boundary of a 50-nm-thick channel of $Sm_{1-x}Ca_xBa_2Cu_3O_y$ (Ca-SBCO). Nakajima *et al.*[7] reported a 5% modulation of critical current on a 60-nm-thick YBCO grain boundary junction channel which can be described by a parallel resistor model. A modulation of several per cent (maximum 8% in I_c) has been reported by Petersen *et al.*[6] on the transport properties of a less than 32-nm-thick YBCO grain boundary junction channel both in the normal and superconducting state. The most recent JoFET experiments were carried out by Mannhart's group[8] where a similar field modulation of I_c was observed. However it is still not clear why all suFETs with grain boundary junction (JoFETs) show much bigger effects than suFETs made of homogeneous film under the same applied field. Candidate explanations include a weakly coupled SNS model in the dirty limit,[4] a parallel resistor model at high bias current, and the electromechanical effect in the dielectric layer at low bias currents.[6] But none of the above gives a quantitative explanation of the dependence of the critical current on the field. The mechanism responsible for this large field effect therefore remains an open and very important question.

In this letter we attempt to clarify this issue, using a phenomenological model based on the Ginzburg–Landau (GL) theory of phase transitions. A similar model has been already developed for the case of $YBa_2Cu_3O_{7-\delta}$ grain boundaries in bicrystals.[9] The basic result of that study was that the oxygen depletion can account for a major portion of the change from weak to strong coupling of grain boundaries, which is experimentally observed[10] as the misorientation angle is increased. The modification of the oxygen content leads to the variation of the critical temperature as a function of distance from the boundary. The detailed way that this occurs is not well understood from a microscopic point of view. The phenomenological approach of Ref. 9 allows one to simulate the behavior of the system in terms of a few measured parameters and to calculate electromagnetic properties. Our aim in this letter is to apply this method to the field effect modulations seen in the JoFETs of Refs. 3 and 4. We demonstrate that the JoFET systems can be fit into the same conceptual framework as the $YBa_2Cu_3O_{7-\delta}$ grain boundaries.

The experimental measurements[3] were taken on hole-overdoped Ca-SBCO bicrystals junctions with 30% doping of Ca ($x=0.3$) at 20 and 4.2 K. The junction itself is a grain boundary with a misorientation of 24°, created by growing the high-T_c film on an $SrTiO_3$ substrate with such a boundary. A schematic view of the experimental setup is shown in Fig. 1. Junctions of this kind in the $YBa_2Cu_3O_{7-\delta}$ system have been shown to be oxygen-deficient[10,11] with a consequent lowering of the critical temperature.

The basic experimental result is the modulation of the (normalized) critical current as a function of the applied gate voltage, as shown in Fig. 2. The input needed for the theory, is the critical temperature T_c as a function of the distance from the boundary plane, and as a function of the applied field. The theory then gives a prediction for the critical current. Detailed work on the effect of doping on the critical temperature of the cuprates[12,13] shows that T_c follows a

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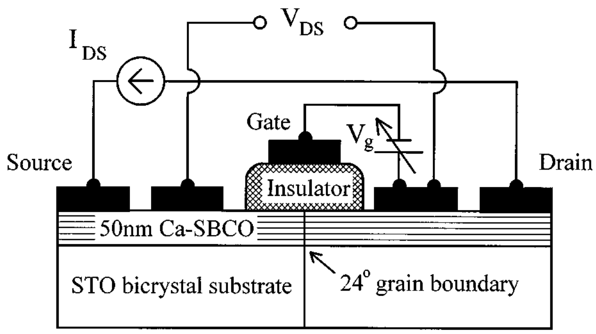

FIG. 1. Schematic view of JoFET and the circuit outline for the field effect measurements.

parabolic relation: $T/T_{c,\max}=1-82.6\times(n-0.16)^2$, where n is the carrier concentration (holes per CuO_2 unit) and $T_{c,\max}=70$ K for the material under study ($Ca_{0.3}Sm_{0.7}Ba_2Cu_3O_y$).[3] From the specific characteristics of the specimen, given that a grain boundary of 24° corresponds to a weakly-coupled bicrystal, then the dependence of the concentration n on the distance follows an exponential function in accordance with the previous work.[9] So at zero applied gate voltage: $n(x)=0.210-0.206\times\exp(-0.2x/\xi)$, where ξ is the superconducting coherence length which has an approximate value of 2 nm.

Also, the effect of the applied gate voltage V_g is taken as a linear contribution in the concentration function, since the induced charge density ΔN for the specific material can be found from the observation that $\Delta N/V_g=C_g/|e|$

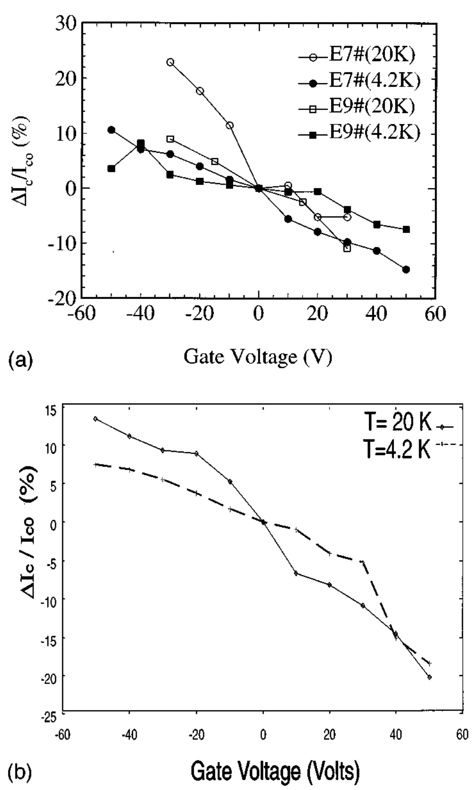

FIG. 2. (a), the experimental data from Ref. 2 (the circles represent the 15 μm wide device and the squares the 30 μm wide device), in (b), the results of the calculations from the (GL) theory for the two experimental temperatures $T=20$ K (solid line) and $T=4.2$ K (dashed line).

$\simeq 3.2\times 10^{11}$ cm^{-2} V^{-1} where C_g is the areal gate capacitance and e is the electron charge. The contribution is then $\delta n=7\times 10^{-5}$ V$^{-1}V_g$.

In the one-dimensional case we consider, the GL free energy that has to be minimized takes the form (we use a gauge where the vector potential $\vec{A}=0$ for convenience, since no magnetic field is present and the free energy is gauge invariant):

$$F=\alpha(x,T)\Psi^2+\frac{\beta'}{2}\Psi^4-\frac{\hbar^2}{2m^*}\left(\frac{d}{dx}\Psi\right)^2, \tag{1}$$

where m^* is the effective mass. We take the following form for $\alpha(x,T)$:

$$\alpha(x,T)=\alpha_0 T_c(x)^2[\tanh(3.0\sqrt{T_c(x)/T_1})]^2 \quad \text{if } T_c>T \tag{2}$$

$$=9\alpha_0 T^2[T_c(x)/T-1] \quad \text{if } T_c<T. \tag{3}$$

This expression for $\alpha(x,t)$ for $T<T_c$ is an analytic fit to the strong-coupling form of the gap function in Bardeen–Cooper–Schrieffer theory. Above T_c, we have less knowledge about the form of the coefficients of GL theory. We have chosen a form for α in this regime guided by two considerations: the expression for α should continue smoothly through T_c, and should be consistent with the equation $\xi=(\hbar^2/2m^*\alpha)^{1/2}$, where ξ is the coherence length. A function different from the usual first order term $(T-T_c)$ in the expansion close to T_c is necessary in order to cover the whole range of temperatures (it is stressed here that T_c varies with the distance). It is obvious that if we expand the above function close to T_c we get the usual $(T-T_c)$ term. β is taken as constant. The theory thus involves the assumption that GL theory may be used over a broad range of temperatures. The great virtue of using this approach instead of a microscopic theory is that the parameters can be related to a number of observable quantities. The above choice has been tested in the successful fitting or prediction of several quantities (calculation of the order parameter, NMR studies, specific heat etc.)[14,15]

It is now convenient to write: $\Psi=|\Psi|\exp(i\phi)$ in which case the current density J is given by: $J=(\hbar e/m^*)\times|\Psi|^2\times d\phi/dx$.

These expressions may be simplified by the definitions: $f(x)=\Psi/\Psi(\infty)$, $h(x)=\alpha(x,T)/\alpha(\infty,T)$, and $j=J/J_c(\infty)$, while x is taken in units of ξ.

Here $J_c(\infty)$ is the bulk depairing current

$$J_c(\infty)=2e|\Psi(\infty)|^2\frac{2}{3}\left(\frac{2\alpha(\infty,T)}{3m^2}\right)^{1/2}. \tag{4}$$

The Euler–Lagrange equation corresponding to the GL free energy in Eq. (1) is the differential equation

$$\frac{d^2f}{dx^2}-(4j^2/27f^3)+h(x)f-f^3=0. \tag{5}$$

The computational problem is to solve the nonlinear differential Eq. (13) with the boundary conditions: $f(\pm\infty)=\sqrt{y}$ and $df(\pm\infty)/dx=0$, where y is the solution of the equation: $y^2-y^3=(4/27)j^2$.

At low current densities j, a superconducting solution exists. The critical current is found by increasing j until no

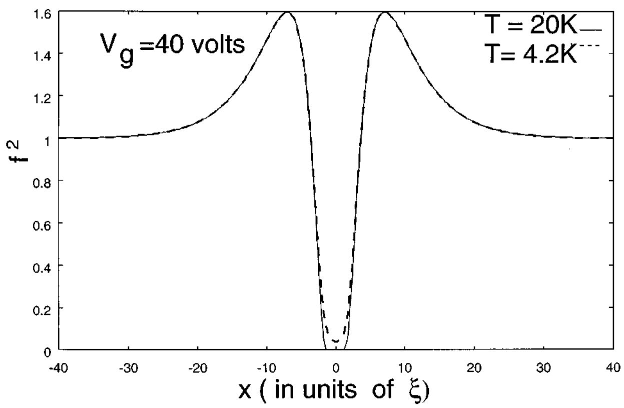

FIG. 3. The calculated order parameter for the gate voltage of 40 V and for the two experimental temperatures 4.2 and 20 K.

superconducting solution exists. This yields the quantity $\Delta I_c/I_{c0}$ where $\Delta I_c = I_c(V_g) - I_c(0) = I_c(V_g) - I_{c0}$. We plot the calculated results together with the experimental data in Fig. 2. It is clear that the model under study can reproduce the basic experimental finding of the large electric field effect on grain boundary Josephson junctions. The results show modulation in critical current from a few percent for small voltages to almost 20% for the largest values that have been used.

The calculation of the order parameter gives a very good picture of the suppression of superconductivity as we approach the boundary (Fig. 3). Interestingly, there is also a region with order parameter values $|\Psi|$ greater than the bulk value of Ψ due to the shape of the function $T_c(x)$, leading to an enhancement of the superconductivity just before the suppression. Temperature plays a more important role in the shape of the order parameter, so at higher experimental temperature there is a well defined nonsuperconducting region close to the grain boundary. The application of the gate voltage alters the critical current which has small effect on the order parameter (due to the fact that it is several order of magnitude less than the depairing current at infinity). This small effect can be barely detected in the asymptotic values of Ψ as well as the value of the peak of Ψ. Furthermore, similar calculations in the underdoped regime (e.g., in an as-made $YBa_2Cu_3O_y$ film on bicrystal) have been performed and the quantity $\Delta I_c/I_{c0}$ shows that this case is less sensitive to the field (about half the modification observed in the overdoped regime).

The calculations demonstrate that if there is relatively weak coupling between the two sides of the boundary, a relatively small modification of the carrier density can have dramatic consequences. The boundary serves effectively as a proximity-effect junction which changes from $S-S'-S$ towards $S-N-S$ as the field is applied. The result is the observed large field effect. Thin films do not show the same effect because the field is being applied to a strong superconducting region.

Another point to emphasize is that the above model does not distinguish between s- or d-wave symmetry of the gap function and consequently of the order parameter. The GL theory has the identical form for the two cases.[14] Thus the actual microscopic mechanism of high-T_c superconductivity does not affect our results.

These results provide guidance for further investigations in this field. The large field effect on JoFETs can be accurately predicted within the Ginzburg–Landau theory while the complications of the microscopic theory are avoided.

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