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HIGH-T_c SUPERCONDUCTING ELECTRONICS: IMPLICATIONS OF REDUCED DIMENSIONALITY

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First, we present experimental evidence that Bi-Sr-Ca-Cu-O superconductors are effectively quasi-two dimensional, in both the normal and the superconducting state. Next, we analyze how this unusual property of the material influences the quest for active electronic components based on high-T_c superconductors, with focus on trilayer Josephson junctions and ferroelectric/superconductor field-effect devices.

I. INTRODUCTION

The first speculations about the two-dimensional (2D) nature of superconductivity in cuprates may be as old as the high-T_c superconductors themselves[1]. More refined theoretical arguments have been offered since[2], but nevertheless the question about the effective dimensionality of the normal and the superconducting states in cuprates is still vividly debated.

The first clear indication that the normal state may be 2D is obtained from polarized reflectance spectroscopy[3a] on single crystals of $Bi_2Sr_2CaCu_2O_8$. As seen from Figure 1, the reflectance is metallic-like for the in-plane polarization, and distinctly insulator-like for the out-of-plane field orientation.

Optical spectroscopy also provides some indication that the superconducting state may be 2D as well. Namely, it enables one to accurately monitor the carrier density in oxide metals, and this technique has been applied[3b] to $La_{1.85}Sr_{0.15}CuO_4$, $YBa_2Cu_3O_7$, $Bi_2Sr_2CaCu_2O_8$, and $Tl_2Ba_2Ca_2Cu_3O_{10}$. T_c is found *not* to scale with the volume carrier density N, but rather with the molecular-layer density n (i.e., the number of mobile charge carriers, per unit area, in one molecular layer), as shown in Figure 2. This suggests a picture in which thin high-T_c superconducting slabs (such as CuO_2-Ca-CuO_2 layers within $Bi_2Sr_2CaCu_2O_8$) are separated by some 'spacer' layers (e.g., BiO-SrO), which can be insulating, semiconducting, or metallic. The point is that, in this picture, T_c is a property of individual superconducting slabs, while the way in which they are coupled should not matter very much.

Other indications for 2D superconductivity have also been found, for example, in the critical current, angular-dependent magnetoresistance, and torque magnetometry data. However, neither of these experiments is quite conclusive; for example, in highly anisotropic systems the out-of-plane resistance is very sensitive to planar defects such as stacking faults and microcracks.

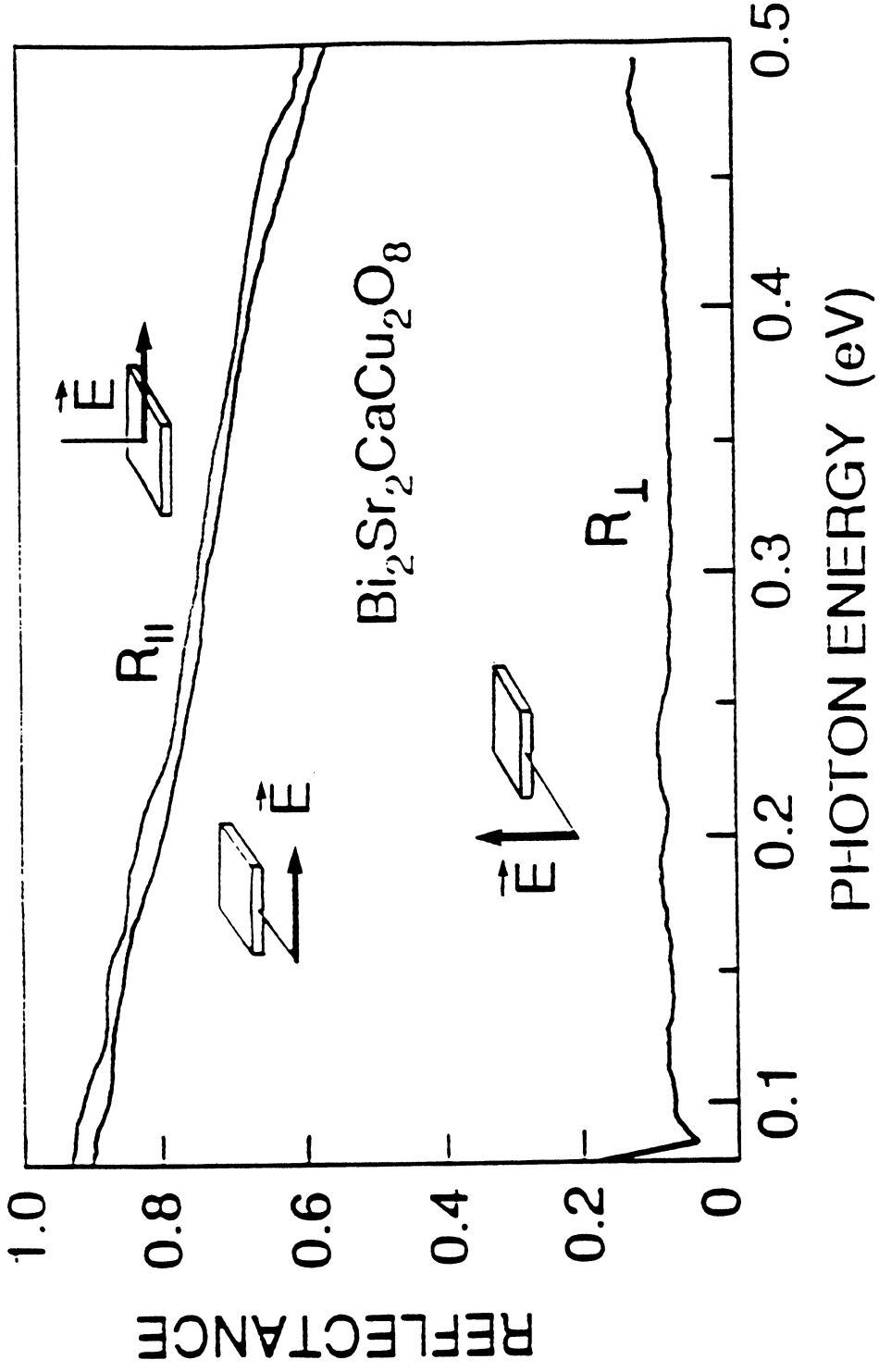


FIGURE 1 The polarized mid-infrared reflectance spectra of single crystals of $Bi_2Sr_2CaCu_2O_8$.

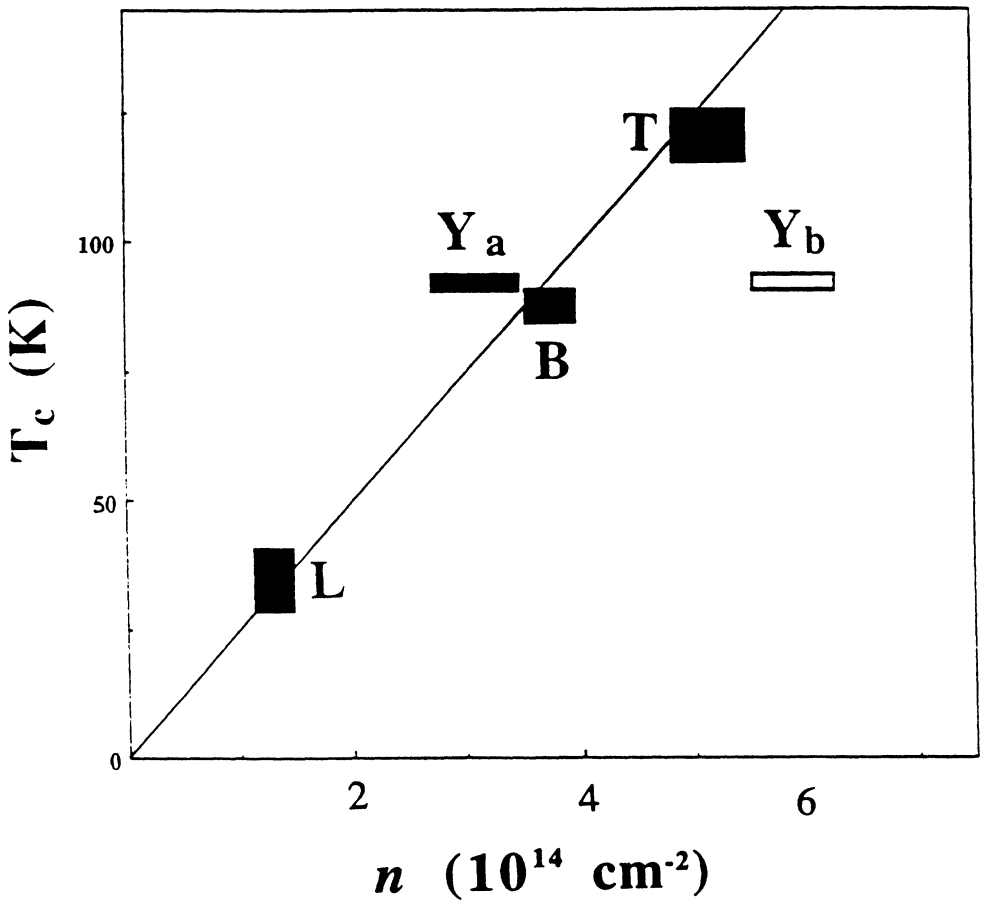


FIGURE 2 T_c as a function of n, the molecular-layer carrier density, in $La_{1.85}Sr_{0.15}CuO_4$ (L), $YBa_2Cu_3O_7$ (Y_a, the contribution from the CuO_2 planes only, solid rectangle; Y_b, the sum of both contributions from planes and chains, open rectangle), $Bi_2Sr_2CaCu_2O_8$ (B), and $Tl_2Ba_2Ca_2Cu_3O_{10}$ (T).

II. EXPERIMENTAL

To overcome such criticism, we have synthesized[4] 'diluted' superlattices in which ultrathin layers of $Bi_2Sr_2CaCu_2O_8$, which has $T_c \approx 85$ K, are separated by up to 120 Å thick layers of $Bi_2Sr_2CuO_6$, with $T_c \approx 15$ K. Indeed, these two compounds are very well matched chemically, crystallographically and electronically. Their *a* and *b* lattice constants are nearly identical, which allows for excellent heteroepitaxy. Furthermore, their charge carrier densities do not differ very much, as seen, for example, from similarity of their optical spectra, and in particular from the fact that their plasma edge frequencies are not very different. In consequence, one does not expect much carrier depletion or accumulation to occur in multilayer structures assembled by stacking layers of these two phases.

The technique we have employed was sequential (atomic-layer-by-layer) molecular beam epitaxy (ALL-MBE) deposition, which we will not describe in detail here since it has been reviewed recently[5]. It is sufficient to point out here that this slow, well-controlled technique provides single-crystal films with atomically flat surfaces and interfaces, and with transport properties, without any post-treatment, that are equal or better than those of bulk single crystals. Furthermore, ALL-MBE enables one to stack molecular or even atomic layers in any desired sequence, and hence it is ideally suited for fabrication of highest quality multilayers and superlattice structures.

III. RESULTS AND DISCUSSION

In Figure 3, we show the four-point-contact resistance data for five Bi-Sr-Ca-Cu-O thin films. The film A contains the $Bi_2Sr_2CuO_6$ phase only, B is a pure $Bi_2Sr_2CaCu_2O_8$ film, and C, D, and E are 1:1, 2:1, and 5:1 superlattices, respectively, of $Bi_2Sr_2CuO_6$ and $Bi_2Sr_2CaCu_2O_8$. Notice that in the film E, one molecular layer (15.4 Å thick) of $Bi_2Sr_2CaCu_2O_8$ alternates with five molecular layers (the total of 5 × 12.3 Å = 61.5 Å) layers of $Bi_2Sr_2CuO_6$. Nevertheless, there is no

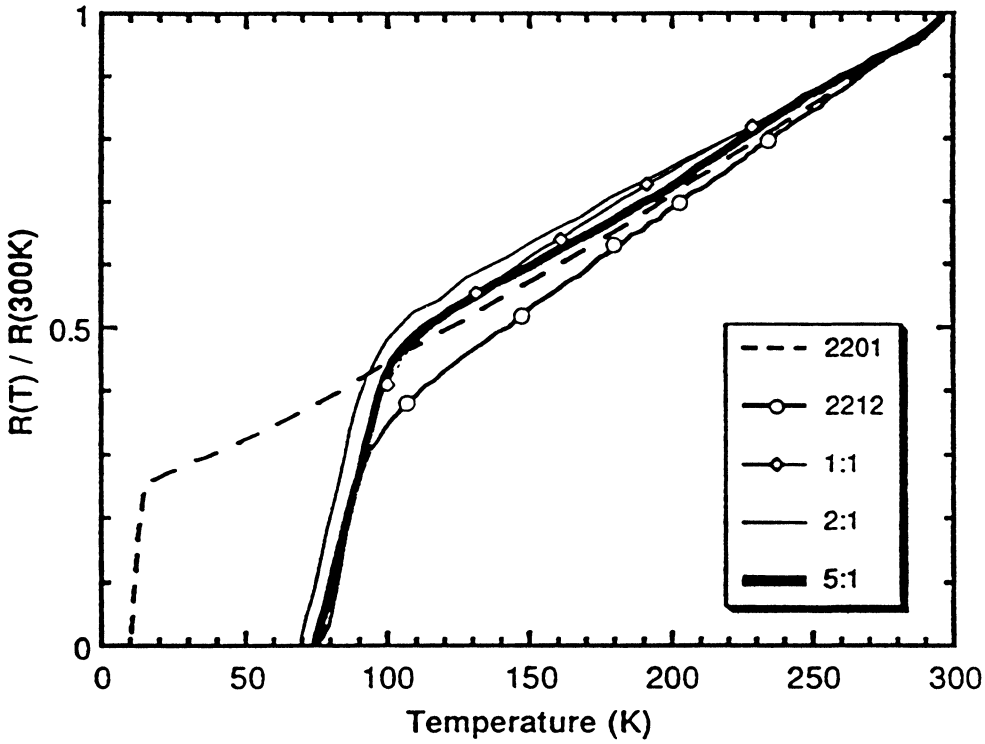


FIGURE 3 Temperature dependence of resistance in (A) 2201 film, (B) 2212 film, (C) 2201:2212 superlattice, (D) (2 × 2201):2212 superlattice, and (E) (5 × 2201):2212 superlattice.

significant decrease of T_c as we increase the number of the spacer layers, which indeed suggests that the interslab coupling is not essential here.

Finally, the most direct approach is to synthesize an ultrathin high-T_c film, ideally containing just one superconducting slab. Generally, this task is quite tedious because of interdiffusion of the substrate material from the bottom side, and oxygen loss, interaction with the atmosphere, etc., from the top side. Yet, ALL-MBE has proven to be up to such a task; using $Bi_2Sr_2CuO_6$ for both the buffer layer and the protecting overlayer, we have succeeded in achieving a remarkably high T_c in a one-unit-cell thick film of $Bi_2Sr_2CaCu_2O_8$, as shown in Figure 4. The transition midpoint, at about 95 K, is actually *higher* than what we observe in thicker films grown under similar conditions. This result leaves very little room for doubts about the essentially 2D nature[6] of high-T_c superconductivity, at least in Bi-Sr-Ca-Cu-O.

Having established this important fact about the superconducting state in cuprates, it is natural to inquire about its implications for various devices that could conceivably be made of these materials. To begin with, let us consider Josephson junctions, focusing on what is commonly referred to as the sandwich-junction geometry. Such junctions, in which a thin insulating barrier layer separates two superconducting layers, have been fabricated quite successfully with conventional, low-T_c superconductors. The principal advantage of this geometry is that, with good epitaxy and growth control, it should provide very reproducible and uniform junctions.

The key technological problem here is to ensure that the superconductor remains undeteriorated in the vicinity of the barrier. What constitutes 'vicinity' turns out to depend on the material, i.e., on its superconducting coherence length, which in low-T_c superconductors is of the order of 10–100 nm. In the case of a high-T_c superconductor such as $Bi_2Sr_2CaCu_2O_8$, the coherence length is much shorter, in particular in the c-axis direction (i.e., perpendicular to CuO_2 planes). Actually, we have already seen that in this material the superconducting slabs are more or less independent, so it will largely be the last molecular monolayer, the one closest to the barrier, that has to ensure that the order parameter is conveyed across the junction. From the materials science point of view, it means that crystalline perfection has to be maintained *on an atomic scale*, in particular near the barrier. Furthermore, the barrier must be made very thin—comparable, perhaps, to one molecular layer of the superconductor—and structurally as perfect itself. Indeed, this is not an easy task; one has to deposit an insulating layer, merely 2–3 nm thick, without any pinholes over large, macroscopic areas.

In Fig. 5, we show some of our data on trilayer Josephson junctions manufactured by ALL-MBE[5]. The top and the bottom electrodes consist of $Bi_2Sr_2CaCu_2O_8$, with $T_c > 80$ K after device fabrication. The barrier consists of a single molecular layer of a phase that is not thermodynamically stable, but which nevertheless can be grown by virtue of atomic layering. Its structure is that of $Bi_2Sr_2Ca_7Cu_8O_{20}$, but trivalent cations (Dy and Bi) are doped to selected Ca sites, to suppress free carriers. [This may be a good illustration of material engineering, by ALL-MBE, at and beyond an atomic monolayer level.] The device structure is illustrated in Fig. 5a; the area of the active mesa is 30 μm $\times$ 30 μm. The junction shows near ideal I-V characteristic, as displayed in Fig. 5b. This way, we believe, the first demonstration of a hysteretic junction made of cuprate superconductors. Very clear mi-

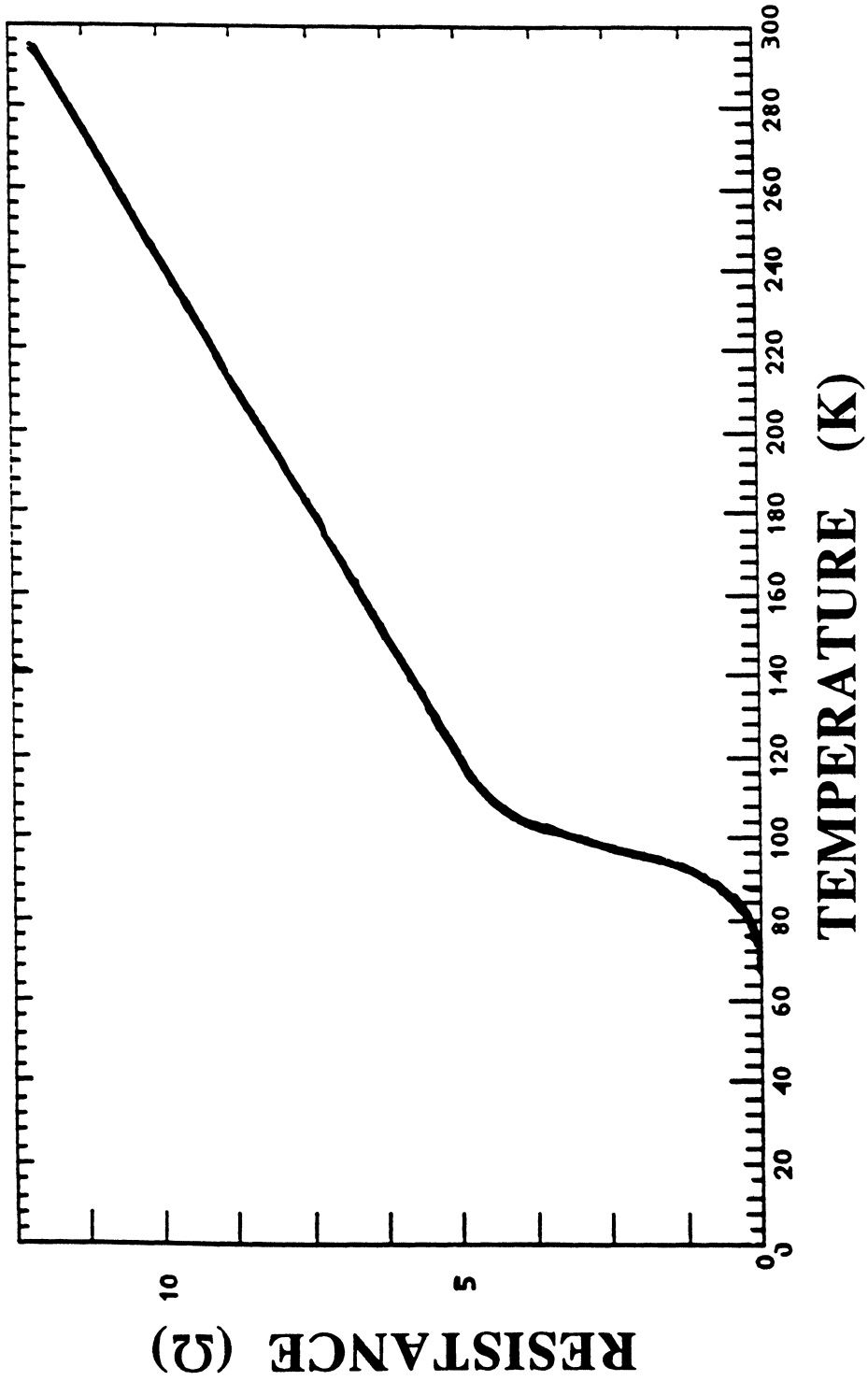


FIGURE 4 Temperature dependence of resistance in film containing a 2201 buffer, a one-unit-cell thick 2212 layer, and a 2201 overlayer.

crowave (Shapiro) steps, as shown in Fig. 5c, are observed in this and other similar devices.

With ALL-MBE, it is possible to control the level of Dy or Bi doping within the barrier, and thus to vary the barrier resistance. [This can be considered as barrier engineering, on an atomic scale.] In this way, the junction critical current and normal state resistance are scaled by over three orders of magnitude, while their product remains nearly constant ($I_cR_n \approx 0.5$ mV). For the most heavily doped barriers, resistance exceeds 10^5 Ω at low temperatures. This shows that there is no leakage due to pinholes or second phase inclusions, over a relatively large area of $(30\ \mu m)^2$, although the barrier thickness is only 25 Å.

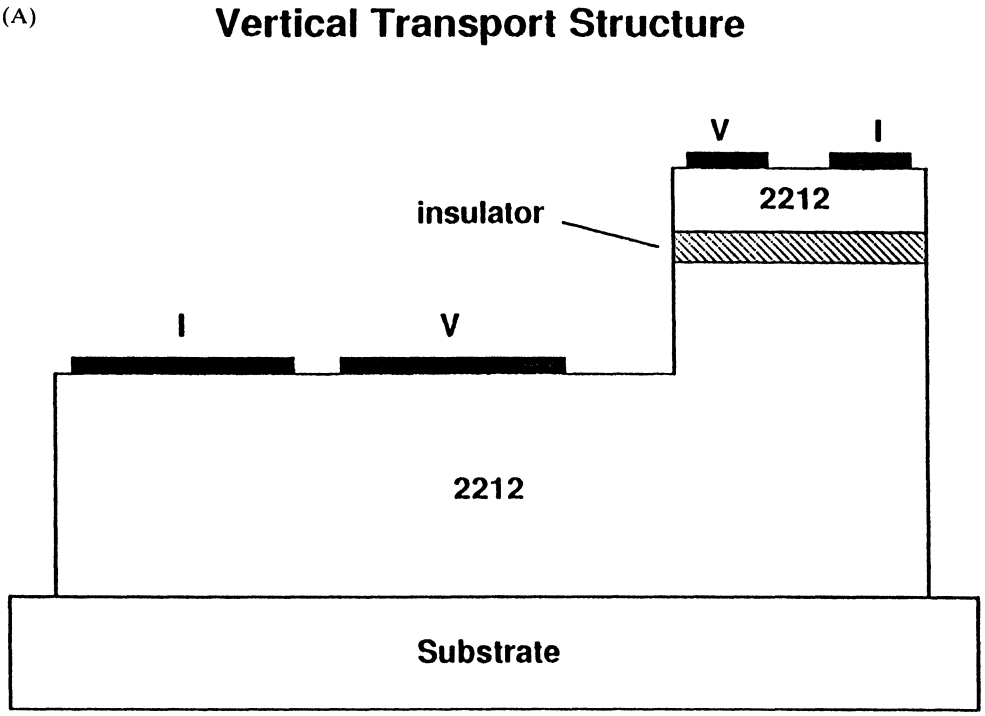
So, we have shown that good trilayer or 'sandwich' Josephson junctions can be manufactured using high-T_c cuprate superconductors. However, admittedly this is not an easy task, and it may call for sophisticated deposition techniques such as ALL-MBE, because, in a sense, one has to work against the 2D nature of the material. [Nevertheless, this avenue undoubtedly deserves to be pursued further, in view of potential payoff of superconducting electronics at liquid nitrogen temperatures.] On the other hand, there exists another class of devices, which we discuss next, in which the reduced dimensionality of high-T_c superconductors is an advantage, and even may be indispensable.

The simplest such device is schematically represented in Fig. 6. This is a three-terminal device, quite similar to a field-effect transistor, in which one is using the electric field to modulate the carrier concentration within the high-T_c layer. Here we actually benefit from the fact that layered cuprates such as $Bi_2Sr_2CaCu_2O_8$ are bad conductors in the c-axis direction, so that the screening length is long and the electric field parallel to that axis can penetrate deeply. Besides, for superconductivity at a high temperature (say, at 77 K), we may need no more one or two molecular layers of $Bi_2Sr_2CaCu_2O_8$, provided one can grow such layers with enough perfection to ensure good connectivity over macroscopic area, and without deterioration of the material's properties. We have seen above that this has been accomplished already. Finally, the carrier density is much lower in cuprates than in the conventional, low-T_c superconductors. It is the fortunate coincidence of these unusual properties—in addition to the potential for operation at liquid nitrogen temperature—that has greatly revived interest in field-effect superconducting devices[7], which were actually proposed long ago.

In the device shown in Fig. 6, we have incorporated two improvements. First, we have added a thick $Bi_2Sr_2CuO_6$ buffer layer. It separates the active layer from the substrate, improves the epitaxy, and facilitates device fabrication, while it does not perturb much the ultrathin high-T_c $Bi_2Sr_2CaCu_2O_8$ layer above it. Furthermore, in this way one has to displace electrons by just few angstroms in order to accomplish carrier depletion or accumulation in the active $Bi_2Sr_2CaCu_2O_8$ layer; the speed of the device is thus increased significantly.

The second modification consists of replacing a simple high-dielectric-strength insulator, as utilized commonly, by a ferroelectric material such as $PbTiO_3$. In a good ferroelectric, spontaneous polarization is large, and the surface charge density can exceed 0.5 C/m^2, while the switching field remains relatively low. In this way, one can considerably reduce the voltage needed to switch the device. With that

(A)



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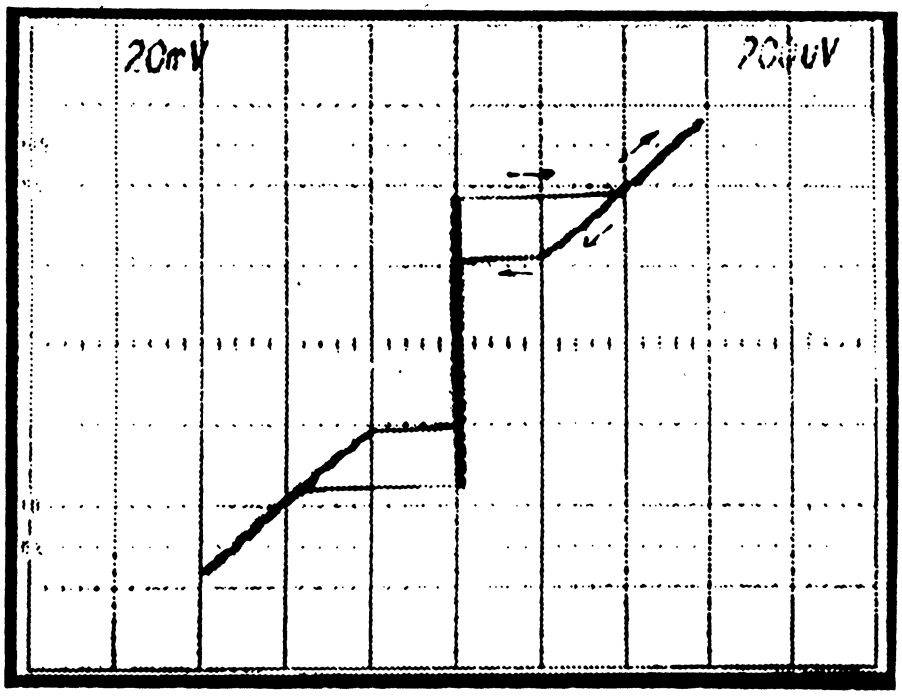
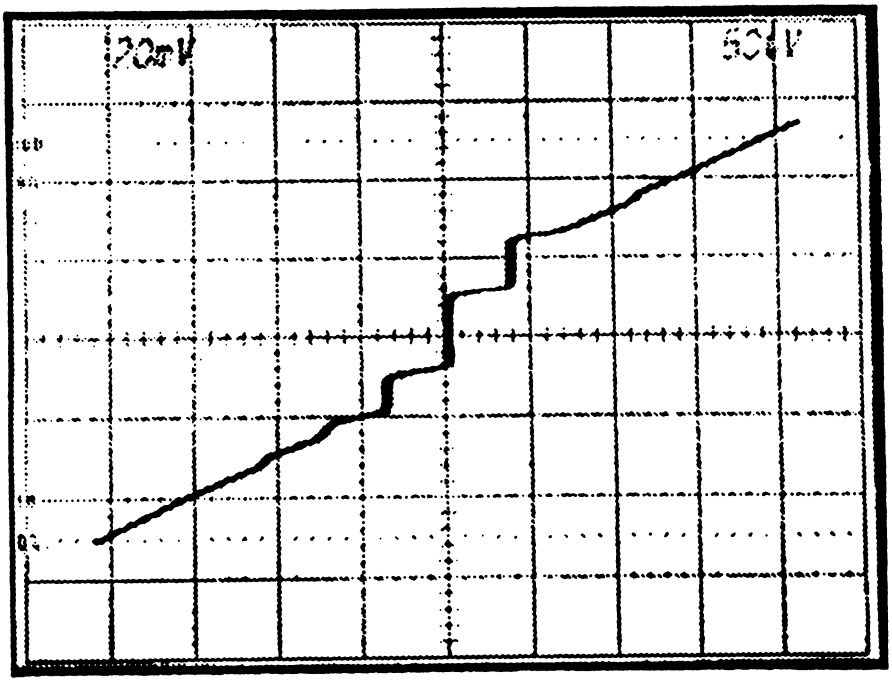


FIGURE 5 (A) A schematic representation of a trilayer Josephson junction device. (B) Current-voltage characteristic of a trilayer Bi-Sr-Ca-Cu-O junction fabricated by ALL-MBE. (C) The same, for device illuminated with 17.9 GHz microwave radiation.

(C)



motivation, we have tried to deposit thin $PbTiO_3$ films on top of $Bi_2Sr_2CuO_6$/ $Bi_2Sr_2CaCu_2O_8$ bilayer films grown by MBE. Highly crystalline, epitaxial thin $PbTiO_3$ films were obtained, so this avenue seems quite promising.

Finally, let us point out that such a device can perform a very different function; it can serve as a fast, nonvolatile, rewrittable memory element. The polarization

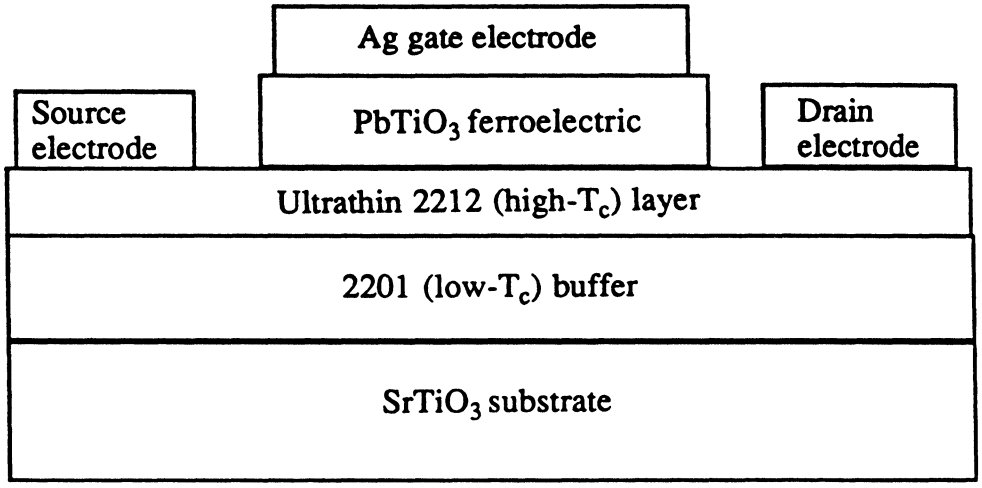


FIGURE 6 A schematic representation of a simple ferroelectric-superconductor field-effect device, FEST (not to scale).

state of the ferroelectric can be switched by a current pulse, and it can be inferred from the voltage across the device. Ideally, if one can sufficiently modulate the carrier concentration within the high-T_c layer, one could switch it between the superconducting state for one polarization of the ferroelectric, and the normal-metal state for the opposite one. In this way, one could read without altering the polarization state, i.e., without erasing. Notice further that a very thin layer of the ferroelectric may be sufficient; the key advantage is that such a layer can be switched very fast, with a voltage as low as 0.1–1 V. This is indeed very convenient for portable systems, for example, so that these and similar devices, still in their infancy, may develop into a mature and useful technology. The future of superconducting electronic components seems bright.

ACKNOWLEDGMENT

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6. More precisely, this should be called *pseudo-* or *quasi*-2D behavior, since one molecular layer of $Bi_2Sr_2CaCu_2O_8$ is about 15.4 Å thick, and furthermore it contains two neighboring (and likely well-coupled) CuO_2 layers.
7. See e.g. J. Mannhart, J.G. Bednorz, K.A. Muller, and D.G. Schlom, Z. Phys. B *83*, 307 (1991), and references therein.