Transistor Performance of High-T_c Three Terminal Devices based on Carrier Concentration Modulation

Koen Joosse, Yurij M. Boguslavskij, Laura Vargas, Gerrit J. Gerritsma, Horst Rogalla
University of Twente, Faculty of Applied Physics, P.O. Box 217, 7500 AE Enschede, The Netherlands

***Abstract*—Electric field effect devices and quasiparticle injection effect devices are good candidates for the realization of three terminal devices from high-T_c materials, since they take explicit advantage of the low carrier concentration in these compounds. We describe the fabrication and operation of both types of devices, and discuss their performance as transistor-like elements.**

I. INTRODUCTION

Superconducting three terminal devices play the role of transistors in superconducting electronics. Ideally they are capable of rapidly switching on and off superconductivity with signal gain. Additionally, superconducting devices should enable operation at low power levels. The availability of such elements would be of great importance for the further development of superconductivity in the field of fast digital electronics [1].

In electric field effect devices a strong electric field perpendicular to the surface of a superconducting thin film modulates the carrier density in the surface layer, thus altering the superconducting properties. Quasiparticle injection devices are based on the creation of a nonequilibrium population of quasiparticles in the superconductor, which suppresses the superconducting properties. Both these devices are promising in high-T_c superconductivity, because the low carrier density in these materials makes it easier to reach either a large change in the average carrier density or a profound nonequilibrium state.

A list of requirements a three terminal device should meet was provided by Gallagher [1]. It includes current, voltage and power gain, high speed, input/output isolation, VLSI density potential, low power consumption and a compatible impedance, while the device should preferably be nonlatching and inverting. Device considerations for field effect devices were given by Mannhart [2] and by Xi *et al.* [3]. Mannhart *et al.* also discussed the transistor potential of a device based on (not yet demonstrated) field induced superconductivity on the surface of an originally non-superconducting sample [4]. Device aspects of classical nonequilibrium superconducting devices were discussed by Buhrman [5].

In this paper we will briefly summarize the results we have obtained on electric field effect and quasiparticle-injection devices. Then we will focus on a discussion on their potential as superconducting transistor-like devices, thereby roughly following [1].

II. ELECTRIC FIELD EFFECT DEVICES

A. Experimental

We have realized electric field effect devices consisting of an ultrathin $YBa_2Cu_3O_x$ (YBCO) layer, *in situ* covered with a $SrTiO_3$ gate insulation layer and a Au gate electrode [6]. In figure 1 a typical set of gate voltage dependent current-voltage characteristics (IVC's) is shown. By applying a gate voltage of 35 V (corresponding to an electric field of $E = 5\times10^6$ V/cm), the average carrier concentration in a typically 5 nm YBCO film can be depleted by ~ 7 %. This corresponds to the depletion of little less than half of the first unit cell from the interface with the gate insulator. This charge depletion causes the critical current to decrease by ~ 15 % at temperatures far below T_c, and up to ~ 80 % close to T_c. In addition, the critical temperature was found to decrease by 1-2 K.

B. Discussion

Some features a transistor should have are perfectly met by these devices. They are nonlatching, and excellent input/output separation is available. The device geometry is relatively simple and scaling down the device dimensions

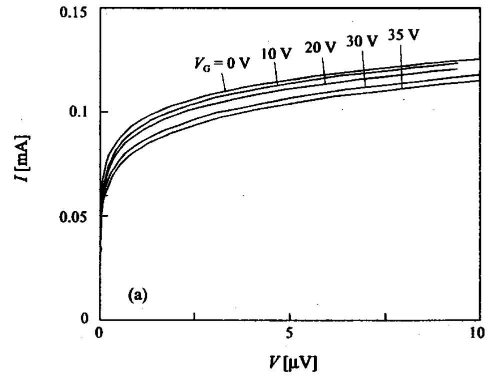

Fig. 1. Effect of electric fields on the current-voltage characteristics of a 5 nm YBCO film.

Manuscript received October 17, 1994. These investigations were performed in the program of the Foundation for Fundamental Research on Matter (FOM) and have been supported by the Netherlands Technology Foundation (STW).

should be quite straightforward.

1*) Operation voltage:* The present devices are certainly not low-voltage devices if the input voltage is considered. To obtain a field of 5 MV/cm over a 70 nm $SrTiO_3$ layer, a gate voltage of 35 V is required. Reducing the thickness of the gate insulator solves this problem partly. However, the main reason for the large gate voltage is the disappointingly low value of the dielectric constant of $SrTiO_3$ thin films, compared to values in excess of 10^4 observed in single crystals. We found $\varepsilon_r(E=0) = 200$, decreasing to $\varepsilon_r(E=10^6\ \text{V/cm}) = 100$. Laser ablated $SrTiO_3$ films tend to have a somewhat larger dielectric constant [7], which indicates that probably the microstructure is an important parameter determining ε_r. On the other hand, the decrease of ε_r in the presence of an electric field is observed in all systems, since the polarization of the dielectric material saturates with increasing field. A search for materials with higher ε_r at low temperatures, which are at the same time compatible with the growth of ultrathin YBCO films seems worthwhile. If deposited as ultrathin films, operating voltages in the 10-100mV-regime appear feasible.

2*) Gain:* Both current and power gain are immediately available, since the leakage current I_G through the gate insulator can be made arbitrarily small. On the other hand, low output voltages are typically obtained in these devices. Dissipation above I_c is determined by vortex motion. The resistivity involved is of the order of the flux flow resistivity, which is much smaller than the normal state resistivity. Also around T_c the apparently attractive switching between states below and above T_c yields only moderate output voltages, due to the typically broad resistive transition of ultrathin YBCO films. The voltage swing between the on- and off-states depends on the bias-point. Generally, one may like to bias well inside the dissipative regime, in order to obtain a linear input/output relation and a large voltage swing. On the other hand, the dissipation increases rapidly, thus reducing the advantage of using superconducting devices in the first place. The resistivity is typically of the order of $\rho \approx 1\ \mu\Omega\,\text{cm}$. The output voltage can be estimated as $V = \rho J_c l$, where l is the device length. If an output voltage of 10 mV is desired, we find $l = 100\ \mu\text{m}$ for $J_c = 10^6\ \text{A/cm}^2$. Although this may not be a problem in applications which do not require a high packing density, it is obviously too large for any application which demands large scale integration. An interesting option might be to use the devices in a background magnetic field. This would increase the flux flow resistivity, $\rho_{ff} = \rho_n B/B_{c2}$, which would allow a further downscaling of the devices.

Larger output voltages would be obtained if the superconductivity in the YBCO film could be completely suppressed into the normal (or insulating) state. Due to the very short screening length, the electric field penetrates the YBCO almost layer by layer, *i.e.* charging of the next layer only starts if the former one is largely depleted. Thus, at low temperatures, where the screening length exceeds the coherence length, shunting by the undepleted part of the YBCO layer requires an almost complete depletion of the carrier concentration in the film to drive it into the normal state. On the other hand, if T_c is approached, the coherence length diverges, and the field effect is expected to average over the sample thickness. In that case, a change in the carrier density of a few tens of % should be enough to move a substantial way along the superconductor's $T_c(n)$-curve. In order to reach such depletion levels, the field effect in the best devices available at present must be increased by another factor of 5 to 10.

3*) Speed:* It has been argued that the operating frequency of electric field effect devices is limited to the sub-GHz range. Both the *RC* charging time and the drift time for carriers to move into and out of the device area were calculated to be in the ns-regime [4]. The drift time, however, may be substantially reduced in a device which is not fully depleted in the dissipative state. In that case, unlike in a conventional semiconducting FET, the field-induced charging can be provided by vertical charge displacement inside the superconducting channel itself, rather than by charge transport from the source and drain electrodes. In combination with the voltage gain requirement we conclude that operation in the vicinity of T_c is preferable, since in this range the increased coherence length enables the suppression of superconductivity without the need of complete charge depletion in the device channel.

The charging time may be reduced by reducing the device dimensions. A $0.5\times0.5\ \mu\text{m}^2$ sized device, with a gate insulator with $\varepsilon_r = 1000$ and $d = 1$ nm has a capacitance as small as 2.2 pF. In addition, a superconducting lead to the gate electrode, and superconductive charging of the channel region may significantly reduce the *RC* charging time.

4*) Power consumption:* Low power consumption should be a major advantage of superconducting electronics. No power is dissipated if the source to drain channel is in the superconducting state. In the dissipative state the power consumption is determined by the resistivity in this state, and by the device dimensions. Assuming that a $1\times1\ \mu\text{m}^2$ sized, 5 nm thick YBCO film with a critical current density of $10^6\ \text{A/cm}^2$ is driven into the normal state, with $\rho \approx 1000\ \mu\Omega\,\text{cm}$, the corresponding power dissipation equals $P = \rho J_c^2 lA = 5\ \mu\text{W}$. The energy dissipated during switching of the device is $E = CV_G^2$, where C is the capacitance. For $C = 2$ pF and $V_G = 50$ mV, we obtain $E = 5\times10^{-15}$ J. Assuming an operating frequency of 1 GHz the corresponding power dissipation is 5 µW. These are indeed low values compared to present day FET's which have dissipation in the 100 µW range [4]. It was pointed out by Kleinsasser *et al.*, however, that the power dissipation in low temperature applications *should* be reduced along with the operating temperature because the ability to remove heat from a wafer scales linearly with temperature [8]. Nevertheless, the dissipation appears to be acceptable.

5) Further: Other parameters determining the device performance include impedance matching to line impedances, noise, integratibility, etc. The impedance can be relatively easily tuned by controlling the device dimensions and appears to offer no complications in the present devices [4]. Care must be taken in the design of densely packed circuits to avoid magnetic interaction between superconducting channels and other lines carrying high current densities.

C. Field effect on grain boundary junctions

It has been argued that Josephson junctions should be more sensitive to electric field effects than the bulk superconducting material, the main reason being a less efficient screening. We have attempted to produce controlled grain boundary junctions with a $SrTiO_3$ insulating layer and a gate electrode. First a 80 nm YBCO layer was grown on a $SrTiO_3$ bicrystal (24°), and structured into a 20 µm wide junction. We observed $T_c = 80$ K, and J_c at 70 K was as high as 2×10^4 A/cm^2. Next, a 40 nm $SrTiO_3$ layer and a Au gate electrode were deposited. We still observed $T_c \approx 80$ K, but severely degraded J_c values: $J_c(30K) = 1.3\times10^3$ A/cm^2. Furthermore had R_N increased from $0.25\,\Omega$ to $13\,\Omega$. We conclude that the deposition of $SrTiO_3$ on YBCO grain boundary junctions degrades the superconducting properties of the weak link. Apparently, increased interdiffusion occurs at the grain boundary region when $SrTiO_3$ is deposited at elevated temperatures.

The breakdown electric field of the $SrTiO_3$ layer was $E \approx 2.5\times10^5$ V/cm, corresponding to a gate voltage of 1 V. However, by applying these voltages we observed no change in either I_c or R_N of the junction. The measurement is shown in figure 2.

The most recent model for grain boundary junctions was given by Moeckly *et al.* and suggests that the weak link is composed of a collection of superconducting filaments with suppressed T_c due to structural defects, oxygen deficiency or disorder at the chain oxygen site [9]. This suggests that the carrier density in the junction area is relatively large, although it may be somewhat smaller than in the bulk superconducting material. This means that thin film junctions and a strong dielectric are still needed to obtain substantial field effects. In addition, voltage gain may be difficult to reach in junction based devices. The output voltage of a channel containing a single junction is limited by the I_cR_N product of the junction, which is typically a few mV's.

III. QUASIPARTICLE INJECTION DEVICES

A. Experimental

The preparation of quasiparticle injection devices has been described in [10]. Briefly, planar YBCO structures were covered with PrBCO and Au respectively to form the injection terminal over a length of 20-30 µm. In order to vary the energy and the spectrum of the injected quasiparticles, the thickness of the PrBCO barrier was varied between 0 and 40 nm. In figure 3 the critical current of a YBCO bridge is shown as a function of the injection current I_G from a Au electrode, *i.e.* $d_{PBCO} = 0$. The asymmetry in this dependence is caused by summation of I_G and the transport current I_s. I_G flowed from the gate electrode to one of the current electrodes of the YBCO bridge, which means that summation of I_G and I_s occurs and influences the behavior of I_c in an asymmetric way If I_G in the channel flows parallel with I_s, the currents add and I_c will decrease by approximately I_G. If I_G flows opposite to I_s, the currents subtract, which leaves I_c practically unchanged.

Besides current summation, current gain, defined as $K = \Delta I_c/I_G$, exceeding unity is obviously obtained: at T=60 K an injection current of 43 mA is sufficient to suppress a critical current of 86 mA to zero, so $K = 2$. The current gain

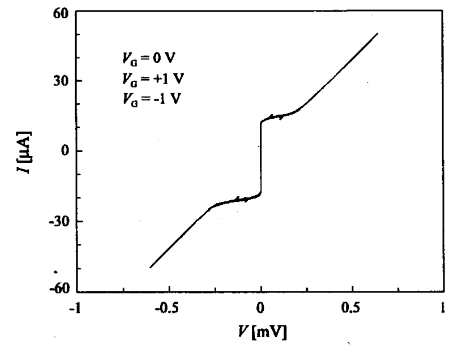

fig. 2: Current-voltage characteristics of a 80 nm thick $YBa_2Cu_3O_x$ grain boundary junction, covered with 40 nm $SrTiO_3$, at T = 32 K. Applied gate voltages of +1 V and -1 V do not change the behavior.

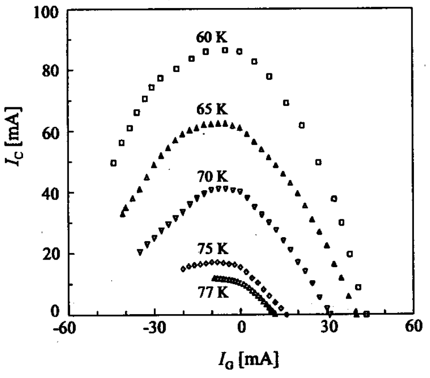

Fig. 3. Dependence of the critical current I_C of a YBCO bridge on the injection current I_G from an YBCO/Au contact at different temperatures.

decreases linearly with increasing temperature, because the already existing thermally excited quasiparticles above the gap make the nonequilibrium effect of the injected quasiparticles less effective. An increase of the PrBCO barrier decreased the current gain, even though the gate voltages were higher. For $d_{PBCO} = 40$ nm no current gain was obtained, *i.e.* $K = 1$, and the behavior of the YBCO under injection was completely determined by current summation. We believe that the energy of the quasiparticles is largely lost in the PrBCO barrier, due to the small average hopping distance in the c-axis direction. On the other hand, the dissipated power $I_G V_G$, is much larger in this case than in the experiment with $d_{PBCO} = 0$. This allowed us to conclude that heating of the structure due to dissipated power is too small to explain the current gain.

B. Discussion

1) Operation voltage: In order to create a quasiparticle population above the energy gap, the injected particles must possess an energy which is at least comparable to the gap. In YBCO this corresponds to a voltage of ~ 20-30 mV at $T = 0$ K [11], which would make the device a low voltage device. If the gate voltage is increased, quasiparticles are injected with a higher energy and can break up additional Cooper pairs, which increases the current gain. It is likely that more efficient injection barriers can be found if high energy quasiparticle injection is desired.

2) Gain: As was shown above, current gain has already been achieved. Since the nonequilibrium effect is expected to scale with the relative amount of excess quasiparticles, the current gain can be increased by decreasing the YBCO thickness or the device length. When current biased at I_c, the output voltage in the dissipative state is $V_{out}=\rho J_c l$. For voltage gain V_{out} should be of the order of 40 mV. With $J_c=5\times10^6$ A/cm^2 and $l=1$ µm, we find that $\rho>80$ µΩ cm is required. This means that a resistivity corresponding to that of the normal state is needed to obtain voltage gain in a device with this size. Alternatively, one may of course reduce the required resistivity by increasing the device length.

3) Power consumption: In a device with both current and voltage gain, dissipation due to current transport is mainly determined by the dissipation in the YBCO-bridge. It is zero in the off-state ($V = 0$) and in the ten µW-regime for a device with $l\times b = 1\times1$ µm^2 and $d = 10$ nm. Switching energies will be small due to the low gate voltages and capacities.

4) Speed: Speed is one of the most interesting aspects of these devices. As was shown in time resolved optical excitation experiments by Shi *et al.* [12], nonequilibrium processes in YBCO films can develop and relax in a time as short as 30 ps. However, if the injection of quasiparticles leads to an increase of the temperature, the relaxation-time is given by the thermal relaxation time, which is in the ns-µs range. In the optical experiment of Shi *et al.* thermal effects did not occur if the laser-power per area was less than 3100 W/cm^2 in a YBCO film of 10 nm thickness. In ourYBCO/Au device, the injected power was only 1500 W/cm^2, in a 50 nm thick film, suggesting that with the power level required for device operation thermal effects could be avoided.

The bolometric response should be avoided if fast device operation is required. Some indication exists that the nonequilibrium response of ultrathin films is mainly of nonbolometric origin [12,13]. Further investigation is needed to elucidate whether the conditions for voltage gain (driving the device into a high resistive state) and fast operation (avoiding thermal effects) can be simultaneously met.

IV. CONCLUSIONS

Superconducting field effect devices are expected to operate as true transistor-like devices, with gain, high speed and low power, if the field induced relative change in the carrier concentration can be increased by another order of magnitude. Furthermore, a gate insulator is needed with a dielectric constant close to 1000, which can be grown as an ultrathin layer on top of YBCO.

Nonequilibrium effects are available in YBCO films under quasiparticle injection. Current gain in devices based on this effect has already been shown. To obtain voltage gain, a device of practical dimensions should probably be switched between superconductivity and the normal state. On the other hand, to avoid a slow response of the devices, thermal effects should absolutely be avoided. The question of whether or not these two conditions are compatible needs further investigation.

REFERENCES

[1] W.J. Gallagher, *IEEE Trans. on Magn.*, MAG-21, p. 709, 1985.

[2] J. Mannhart, *Appl. Supercond. (Proc. EUCAS '93)* Vol 2, p. 1461, 1993.

[3] X.X. Xi, *presented at Conf. on Phys. and Chem. on Molecular and Oxide Supercond.*, Eugene, 1993, preprint, X.X. Xi, C. Doughty, A. Walkenhorst, S.N. Mao, Q. Li, T. Venkatesan, *Appl. Phys. Lett.* Vol. 61, p. 2352, 1992.

[4] J. Mannhart, A.W. Kleinsasser, *Proc. MRS Spring Meeting*, San Francisco, 1992.

[5] R.A. Buhrman, in *SQUID 85*, Berlin: W. de Gruyter & Co., 1985.

[6] K. Joosse, Yu.M. Boguslavskij, G.J. Gerritsma, H. Rogalla, *Physica C*, Vol 224, p. 179, 1994.

[7] C. Doughty, A. Walkenhorst, X.X. Xi, C. Kwon, Q. Li, S. Bhattacharya, A.T. Findikoglu, S.N. Mao, T. Venkatesan, K.A. Feldman, N.D. Spencer, *IEEE Trans. on Appl. Supercond.*, Vol. 3, p. 2910, 1993.

[8] A.W. Kleinsasser, W.J. Gallagher, in *Superconducting Devices*, Boston: Academic Press, 1990.

[9] B.H. Moeckly, D.K. Lathrop, R.A. Buhrman, *Phys. Rev. B*, Vol. 47, p. 400, 1993.

[10] Yu.M. Boguslavskij, K. Joosse, F.J.G. Roesthuis, G.J. Gerritsma, H. Rogalla, *Physica C*, Vol. 220, p. 195, 1994.

[11] M.M. Meyer III, J.H. Weaver, in *Physical properties of High-T_c supercond.*, Vol. II, Singapore: World Scientific, 1990.

[12] L. Shi, G.L. Huang, C. Lehaene, D.H. Kim, H.S. Kwok, *Appl. Phys. Lett.*, Vol. 63, p. 2831, 1993.

[13] A.P. Zhuravel, K. Joosse, G.J. Gerritsma, A.G. Sivakov, I.M. Dmitrenko, *presented at ICEC 15*, Genoa, 1994.