

the electric field-effect in copper oxide compounds have been reported (for example by U. Kabasawa et al. in Japanese Journ. of Appl. Phys. 29 L86, 1990), but so far only minor field-effects in high- T_c superconductors have been found. However, EP-A-0 324 044 already describes a three-terminal field-effect device with a superconducting channel in which electric fields are used to control the transport properties of channel layers consisting of high- T_c superconductor materials. While this seemed to be a promising approach, growth studies of such devices have shown that in the suggested configuration the ultrathin superconducting layers readily degrade during deposition of insulator layer and top electrode.

It is an object of the present invention to ameliorate one or more disadvantages of the prior art.

According to one aspect of the present invention there is provided a superconductor field-effect transistor comprising: an electrically conductive substrate of a single crystal of a material of a crystallographic family, said material consisting of niobium-doped strontium titanate Nb:SrTiO_3 , with a doping factor of between 0.001% and 10% niobium, said crystal having a predetermined crystallographic orientation; a gate electrode being formed by a contact to said substrate; an insulating barrier layer on a top surface of said substrate, said insulating barrier layer being a second material of said crystallographic family and having the same said predetermined crystallographic orientation; a superconducting thin film layer on a top surface of said insulating barrier layer; a pair of gold pads on a top surface of said superconducting thin film, a first said gold pad being a source electrode and a second said gold pad being a drain electrode; and, an electrical-field-controlled current channel in said superconducting thin film layer between said pair of gold pads.

According to another aspect of the present invention there is provided a superconductor field-effect transistor comprising: an electrically conductive substrate of a single crystal of a first material of a crystallographic family, said crystal having a predetermined crystallographic orientation; a gate electrode being formed by a contact to

said substrate; an insulating barrier layer on a top surface of said substrate, said insulating barrier layer being a second material of said crystallographic family and having the same said predetermined crystallographic orientation, said second material consisting of strontium titanate SrTiO_3 having a $\{100\}$ crystallographic orientation, and being between 0.3 and 100 nm thick; a superconducting thin film layer on a top surface of said insulating barrier layer; a pair of gold pads on a top surface of said superconducting thin film, a first said gold pad being a source electrode and a second gold pad being a drain electrode; and, an electrical-field-controlled current channel in said superconducting thin film layer between said pair of gold pads.

According to still another aspect of the present invention there is provided a superconductor field effect transistor comprising: an electrically conductive substrate of a single crystal of a first material of a crystallographic family, said crystal having a predetermined crystallographic orientation; a gate electrode being formed by a contact to said substrate; an insulating barrier layer on a top surface of said substrate, said insulating barrier layer being a second material of said crystallographic family and having the same said predetermined crystallographic orientation; a superconducting thin film layer on a top surface of said insulating barrier layer; a pair of gold pads on a top surface of said superconducting thin film, a first said gold pad being a source electrode and a second said gold pad being a drain electrode; and, an electrical-field-controlled current channel in said superconducting thin film layer between said pair of gold pads.

According to still another aspect of the present invention there is provided a superconducting field-effect transistor comprising: substrate consisting of a layer of gold on an underside of an insulating layer; a superconductive thin film on a top side of said insulating layer; a pair of electrodes on said superconductive thin film; and a contact on said layer of gold.

According to still another aspect of the present invention there is provided a method for making a field-effect transistor having an electrical field-controlled current channel and gate, source and drain electrodes comprising the steps of: a) providing a

gate electrode (2) of a conductive n-type {100} oriented Nb-doped SrTiO_3 single crystal that has a doping factor between 0.001% and 10% niobium, said gate electrode serving as a substrate; b) depositing on top of said gate electrode (2) a {100}-oriented insulating layer (3) of SrTiO_3 ; c) depositing on top of said insulating SrTiO_3 layer (3), a superconducting thin film (1) of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, wherein $0 \leq \delta \leq 0.5$; d) depositing onto said $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ layer (1) gold pads (4,5) to form source and drain contacts, respectively; and e) depositing a gate contact (6) on the Nb-doped SrTiO_3 gate/substrate (2).

According to yet another aspect of the present invention there is provided a method for making a field-effect transistor having an electrical-field-controlled current channel and gate, source and drain electrodes comprising the steps of: a) providing a {100}-oriented SrTiO_3 layer (7) as an insulator and thinning said layer down to a thickness of 20 to 30 μm ; b) sputtering on top of the thinned insulator (7), a $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film (8), wherein $0 < \delta < 0.5$ the thickness of said sputtered film (8) being in the range of 1 to 10 nm; c) providing metal pads (9, 10) on top of the superconductor layer (8) to form source and drain contacts, respectively; d) depositing a gate electrode (11) onto the back side of the thinned insulator (7) in form of a metal layer; and e) applying a contact (12) at the underside of said gate electrode (11).

The use of niobium-doped strontium titanate Nb: SrTiO_3 in a high- T_c superconductor structure was described by H. Hasegawa et al. in their paper "Contact between High- T_c Superconductor and Semiconducting Niobium-Doped SrTiO_3 ", Japanese Journ. of Appl. Phys., Vol. 28, No. 12, Dec. 1988, pp. L 2210-L 2212, and in their EP-A-0 371 462. These references describe a diode structure where a superconducting film is deposited onto an Nb-doped SrTiO_3 substrate. The authors of these references are only interested in measuring the rectifying properties and the resistance in forward and reverse directions. They "demonstrated that there are unknown interfacial layers between the two materials", a problem that the present invention elegantly overcomes.

which electrostatic fields are screened in conducting materials is given by the sum $L_D + L_{DZ}$ of the Debye length $L_D = (\epsilon_0 \epsilon_r kT / q^2 n)^{1/2}$ and the width of eventual depletion zones $L_{DZ} = N/n$. Here, ϵ_0 and ϵ_r are the dielectric constants of the vacuum and of the conducting material, respectively, k is the Boltzmann constant, T is the absolute temperature, q is the elementary charge, n is the density of mobile carriers, and N the induced areal carrier density. Because of their high carrier density, low- T_c superconductors usually screen electric fields so well that the fields only have a minor influence on materials properties. To attenuate the screening, recent experiments on the electric field-effect in low- T_c superconductors have focused on compounds with exceptionally low carrier density, like doped SrTiO_3 , with niobium as the dopant, for example.

In high- T_c superconductor compounds, larger field-effects are expected owing to their intrinsically low carrier concentration and because of their small coherence length. The low carrier concentration of about $3 \dots 5 \times 10^{21} / \text{cm}^3$ leads to screening lengths in the range of tenths of nanometers, and the small coherence lengths allow the fabrication of ultrathin layers with respectable critical temperatures. Superconducting films as thin as 1...2 nm have already been grown; electric fields can penetrate such films to a considerable extent.

Details of two embodiments of the transistor and of the inventive method will hereafter be explained by way of example, with reference to the attached drawings in which:

Fig. 1 is a schematic diagram of a first embodiment of a field-effect transistor in accordance with the invention;

Fig. 2 is a schematic diagram of a second embodiment of an inventive field-effect transistor;

Fig. 3 shows the I_G/V_G characteristics of the field-effect transistor of *Fig. 1*;

Fig. 4 is a diagram showing the dependence of the changes of the channel resistivity as a function of the gate voltage V_G ;

Fig. 5 shows the dependence of the channel resistivity as a function of the absolute temperature.

To apply large electric fields on thin films of superconducting $\text{YBa}_2\text{Cu}_3\text{O}_7$, in accordance with the invention, an inverted MISFET-structure as shown in *Fig. 1* is used. In this structure, a superconducting film 1 of the thickness s is separated from a gate electrode 2 by an insulating layer 3 of the thickness t . Besides the thickness of the superconductor, the resistivity ρ_i and the breakthrough field strength E_{BD} of the insulator are crucial parameters. The required values for E_{BD} and for ρ_i can be simply estimated, if space charge effects are neglected: To induce a surface charge density in superconducting film 1 which corresponds to the unperturbed density n of mobile charge carriers, the capacitor consisting of gate electrode 2 and superconductor film 1 has to be biased with a voltage

CLAIMS

1. A superconductor field-effect transistor comprising:

an electrically conductive substrate of a single crystal of a material of a crystallographic family, said material consisting of niobium-doped strontium titanate Nb:SrTiO_3 , with a doping factor of between 0.001% and 10% niobium, said crystal having a predetermined crystallographic orientation;

a gate electrode being formed by a contact to said substrate;

an insulating barrier layer on a top surface of said substrate, said insulating barrier layer being a second material of said crystallographic family and having the same said predetermined crystallographic orientation;

a superconducting thin film layer on a top surface of said insulating barrier layer;

a pair of gold pads on a top surface of said superconducting thin film, a first said gold pad being a source electrode and a second said gold pad being a drain electrode; and,

an electrical-field-controlled current channel in said superconducting thin film layer between said pair of gold pads.

2. A field effect transistor as in claim 1 wherein said doping factor of Niobium is 0.05%.

3. A field-effect transistor as in claim 1 wherein the crystallographic orientation of said substrate is {100}.

4. A field-effect transistor as in claim 1 wherein said contact to said substrate forming the gate electrode consists of silver diffused in said substrate.

5. A superconductor field-effect transistor comprising:

an electrically conductive substrate of a single crystal of a first material of a crystallographic family, said crystal having a predetermined crystallographic orientation;

a gate electrode being formed by a contact to said substrate;

an insulating barrier layer on a top surface of said substrate, said insulating barrier layer being a second material of said crystallographic family and having the same said

predetermined crystallographic orientation, said second material consisting of strontium titanate SrTiO_3 having a {100} crystallographic orientation, and being between 0.3 and 100 nm thick;

a superconducting thin film layer on a top surface of said insulating barrier layer;

a pair of gold pads on a top surface of said superconducting thin film, a first said gold pad being a source electrode and a second gold pad being a drain electrode; and,

an electrical-field-controlled current channel in said superconducting thin film layer between said pair of gold pads.

6. A superconductor field effect transistor comprising:

an electrically conductive substrate of a single crystal of a first material of a crystallographic family, said crystal having a predetermined crystallographic orientation;

a gate electrode being formed by a contact to said substrate;

an insulating barrier layer on a top surface of said substrate, said insulating barrier layer being a second material of said crystallographic family and having the same said predetermined crystallographic orientation;

a superconducting thin film layer on a top surface of said insulating barrier layer;

a pair of gold pads on a top surface of said superconducting thin film, a first said gold pad being a source electrode and a second said gold pad being a drain electrode; and,

an electrical-field-controlled current channel in said superconducting thin film layer between said pair of gold pads.

7. A field-effect transistor as in claim 6 wherein the crystallographic orientation of said substrate (2) is {100}.

8. A field-effect transistor as in claim 6 wherein said contact (60 to said substrate (2) forming the gate electrode consists of silver diffused in said substrate (2).

9. A superconducting field-effect transistor comprising:

substrate consisting of a layer of gold on an underside of an insulating layer;

a superconductive thin film on a top side of said insulating layer;

a pair of electrodes on said superconductive thin film; and

a contact on said layer of gold.

10. A field-effect transistor as in claim 9, said superconductor layer (1, 8) consisting of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, wherein $0 \leq \delta \leq 0.5$ and said superconductor layer has a thickness in the range of 1 to 30 nm.

11. A method for making a field-effect transistor having an electrical field-controlled current channel and gate, source and drain electrodes comprising the steps of:

a) providing a gate electrode (2) of a conductive n-type {100} oriented Nb-doped SrTiO_3 single crystal that has a doping factor between 0.001% and 10% niobium, said gate electrode serving as a substrate;

b) depositing on top of said gate electrode (2) a {100}-oriented insulating layer (3) of SrTiO_3 ;

c) depositing on top of said insulating SrTiO_3 layer (3), a superconducting thin film (1) of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, wherein $0 \leq \delta \leq 0.5$;

d) depositing onto said $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ layer (1) gold pads (4,5) to form source and drain contacts, respectively; and

e) depositing a gate contact (6) on the Nb-doped SrTiO_3 gate/substrate (2).

12. A method as in claim 11, wherein said layer (3) of SrTiO_3 is epitaxially grown by reactive rf-magnetron sputtering at 6.7 Pa in an O_2 /Ar atmosphere at 400° to 900° C.

13. A method as in claim 11, wherein said superconducting film (1) of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ is epitaxially grown on top of the insulating SrTiO_3 layer (3).

14. A method as in claim 11, wherein said gate contact (6) is provided by diffusing silver into the Nb-doped SrTiO_3 gate/substrate (2).

15. The method as in claim 11 wherein said doping factor is 0.05% Nb.

16. A method for making a field-effect transistor having an electrical-field-controlled current channel and gate, source and drain electrodes comprising the steps of:

a) providing a {100}-oriented SrTiO_3 layer (7) as an insulator and thinning said layer down to a thickness of 20 to 30 μm ;

b) sputtering on top of the thinned insulator (7), a $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ film (8), wherein $0 < \delta < 0.5$ the thickness of said sputtered film (8) being in the range of 1 to 10 nm;

c) providing metal pads (9, 10) on top of the superconductor layer (8) to form source and drain contacts, respectively;

d) depositing a gate electrode (11) onto the back side of the thinned insulator (7) in form of a metal layer; and

e) applying a contact (12) at the underside of said gate electrode (11).

17. A method as in claim 16, further comprising, providing an insulating substrate (13) under said gate electrode (11).