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A MINIATURIZED APPROACH TO THE CRYOELECTRONIC MAGNETIC FIELD EFFECT TRANSISTOR

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Résumé - Le contrôle magnétique du courant filamentaire pendant le perçement avalanchal dans semiconducteurs à basses températures représente un principe d'opération intéressant pour le dessin d'un transistor basé sur l'effet d'un champ magnétique. Nous avons vérifié expérimentalement des configurations réduites en utilisant des lignes superconductives pour la production d'un champ magnétique et de tous les intermédiaires. L'évaluation des performances caractéristiques importantes de notre conception du transistor paraît être très prometteuse.

Abstract - Magnetic control of the filamentary current flow during avalanche breakdown in bulk semiconductors at low temperatures represents an interesting operation principle for the design of a magnetic field effect transistor. We have experimentally verified miniaturized device configurations using superconducting lines for the generation of the magnetic control field and all interconnections. The evaluation of the important performance characteristics of our transistor concept looks highly promising.

1 - INTRODUCTION

Electrically driven into the regime of low-temperature avalanche breakdown, homogeneously doped semiconductors have been demonstrated to display spatially inhomogeneous current flow via high-conductivity filament channels generated by impurity impact ionization /1-3/. If an external magnetic field is applied perpendicular to the current direction, the current filaments are structurally changed due to the Lorentz force acting upon the moving charge carriers. The corresponding shift of the current-voltage characteristic (magnetoresistance) results from the "cooling effect" of the magnetic field on the hot charge carriers. At low temperatures where the carrier mobility and, hence, the Lorentz force is high, a relatively large magnetoresistance is obtained with applied magnetic fields as small as only a few Gauss. The sensitive response to the magnetic control field offers an interesting principle for the design of a cryoelectronic device family.

As a first experimental approach, we have recently demonstrated the basic concept of a magnetic field effect transistor at liquid-helium temperatures, using single-crystalline p-doped germanium with an acceptor concentration of about 10^{14} cm^{-3} and the typical dimensions of $0.1 \times 5 \times 6 \text{ mm}^3$ /4,5/. The magnetic control of the filamentary current flow was achieved by a small magnetic field (10 - 100 G), generated by superconducting lines attached to the surface of the semiconductor crystal. In this way, a three-terminal device is obtained, based on a hybrid concept implementing semiconducting and superconducting components. Particularly attractive features of this configuration are its simplicity, the utilization of well-established semiconductor and superconductor technology, and its robust nature, promising a high production yield. Moreover, our device concept may become essential in the development of ultrafast electronic circuits, requiring high packing density and correspondingly lower power dissipation.

In order to evaluate the limitations of the important performance characteristics, we have experimentally performed a miniaturized approach to the cryoelectronic magnetic field effect transistor. Using different sample geometries, the distance between the ohmic contacts was reduced systematically, ending up with a minimum value of 10 μm . As expected from a preliminary estimate /6/, the limitations due to the time of flight per length of the carriers and due to the power losses per distance between the ohmic contacts were found to be about 50 ps/ μm and 0.5 $\mu\text{W}/\mu\text{m}$, respectively. Thus, the miniaturized sample geometry enables operation up to frequencies in the GHz regime.

2 - EXPERIMENTAL METHODS

The samples investigated were prepared from homogeneously p-doped germanium single-crystal slices.⁽¹⁾ The specific resistivity at room temperature ranged from 10 to 20 Ωcm , corresponding to an impurity concentration of $(2 - 3) \times 10^{14} \text{ cm}^{-3}$. The compensation ratios were definitely smaller than 5×10^{-2} . The semiconductor samples (of about 0.1 mm thickness) carried properly arranged ohmic contacts placed on one of the two broad surfaces. The distance between the contacts varied from 0.5 mm to 10 μm . The ohmic contacts were fabricated either by alloying (aluminum) or by ion implantation (boron) /7/. To provide these contacts with an electric field, a voltage bias was applied to a series combination of the sample and an 1 Ω load resistor. The sample current was obtained from the voltage drop at the load resistor. An external magnetic field perpendicular to the broad sample surfaces could be generated either by a superconducting coil surrounding the semiconductor sample or by a superconducting loop attached directly to the surface of the sample. Shaped in the form of a long hairpin, the superconducting niobium lines were fabricated by standard thin-film technology, and electric separation from the underlying semiconductor was achieved by a thin-film insulator. During the experiments, the samples investigated were kept in direct contact with the liquid-helium bath at 4.2 K and were protected against external visible and far-infrared irradiation by an appropriate copper shield.

3 - EXPERIMENTAL FINDINGS AND DISCUSSION

As already mentioned above, the operating principle of the present transistor device is based on the magnetic control of the filamentary current flow during low-temperature avalanche breakdown via the magnetoresistive effect. Since the magnetic field needed for magnetic control is found to be inversely proportional to the mobility of the charge carriers, the required high magnetic field sensitivity of the current flow can only be attained at high carrier mobility. With reference to the experimental verification of extremely high carrier mobilities and drift velocities (of some $10^5 \text{ cm}^2/\text{Vs}$ and some 10^6 cm/s , respectively)/8/, adequate magnetic control can be achieved already with small magnetic fields in the range of 100 G. In the following, we briefly outline a quantitative evaluation of the most important performance characteristics based on an experimental realization of distinct miniaturized device geometries.

We emphasize that the two essential preconditions of our transistor scheme, namely, first, the appearance of the avalanche breakdown effect and, second, the magnetic control of the current flow in the breakdown regime, have been verified for all samples investigated. For relatively large distances between the ohmic contacts in the range of some 100 μm , differently prepared contacts always led to more or less the same results. But for distances smaller than 100 μm , only samples with ion-implanted contacts showed the expected linear dependence of the breakdown voltage on the contact distance. (Note that such miniaturized geometries are already influenced by the less sharp-edged structure of the heat-treated alloy contacts). By extrapolating the linear voltage versus distance characteristic to zero contact distance, we always found an excess breakdown voltage of about 30 mV. Accordingly, the breakdown electric field strength at small contact distances increases with decreasing distance, ending up with an extrapolated divergence at zero distance. We feel that the existence of an excess breakdown voltage can be directly attributed to the finite ionization energy of the shallow impurities (in the range of 10 meV). Note that avalanche breakdown only occurs if the conduction carriers have gained sufficient kinetic energy from the applied electric field, which at least must be of the order of the impurity ionization energy.

Now we turn to the performance limitations of our transistor scheme due to the time of flight per length of the carriers and due to the power losses per distance between the ohmic contacts. From measured drift velocities of a few 10^6 cm/s in the post-breakdown region /8/ we derive values of about 50 ps/ μm for the time of flight per unit length. This estimate agrees reasonably well with the experimentally observed frequency limits of about 10 MHz up to a few GHz for samples with lengths ranging from 0.5 mm to 10 μm , respectively. We have checked that the above high-frequency limits are definitely not influenced by the capacities and inductivities of the electronic circuit configuration, as expected /6/. With the typical electric field of about 5 V/cm for establishing avalanche breakdown and typical current values of about 1 mA in the immediate post-breakdown region, we obtain for the power losses per sample length values of about 0.5 $\mu\text{W}/\mu\text{m}$, independent of frequency. Taking further into account the increased electric breakdown field at contact distances smaller than 50 μm , the power losses accordingly increase by a factor of five at most. From this we conclude that miniaturization of the transistor device appears to be limited reasonably at the smallest distance of the ohmic contacts chosen (10 μm).

(1) Device applications based on extrinsic silicon and gallium arsenide semiconductors are presently also investigated, but not reported here.

Finally, we point out that the functioning of the present transistor scheme can also be confined by noise problems. On one hand, thermal noise is expected to be small due to the operation at liquid-helium temperatures. But, on the other hand, the possible contribution of additional noise generated by the avalanche process /9/ requires further experimental studies and perhaps additional optimization procedures. Crosstalk between the elements of large integrated systems can be minimized by properly arranged superconducting screening lines. Here important concepts can be taken from the well-established Josephson technology. Nevertheless, unwanted stray magnetic and electric coupling sets a fundamental limit to further miniaturization of all presently used circuitry, that is likely to be reached before the limits imposed in the future by modern microfabrication techniques.

4 - CONCLUSIONS

The present work deals with the first experimental realization of a cryoelectronic magnetic field effect transistor based on a novel hybrid configuration of both semiconducting and superconducting components. We have modeled and characterized miniaturized solid state devices using extrinsic germanium semiconductors together with superconducting niobium lines for generating the magnetic control field and for all interconnections. The evaluation of the important performance characteristics of our transistor concept looks very promising. The power losses of such a device are similar to those in a superconducting Josephson junction, representing the high-speed device with the lowest power consumption up to now. We take note of the fact that superconducting wiring can preserve extremely fast pulse rise times required in ultrafast electronic systems. In this way, combining semiconducting device components operating at low temperature with superconducting lines for magnetic control and for all interconnections represents a highly promising new direction which has been neglected so far and which definitely deserves much more consideration.

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