Extended Abstracts of the 21st Conference on Solid State Devices and Materials, Tokyo, 1989, pp. 261-264

Ballistic Impurity Level Transistor for Superconducting Transistor Applications

Jun'ichi Sone
Microelectronics Research Labs., NEC Corporation
Miyukigaoka 34, Tsukuba-shi, Ibaraki, 305 Japan
02975-7-1164

The electrical characteristics of a ballistic impurity level transistor made of Ge with NbN superconducting interconnection lines operating at 10 K are studied theoretically. This transistor operates with a logic swing of 10 mV corresponding to a impurity binding energy in Ge. The voltage drops due to parasitic resistances between the transistor and the superconductor is small enough to give almost no effect on the transistor action. Due to the small logic swing, the transistor has extremely small dissipation power and interconnection delay.

1. INTRODUCTION

The tremendous reduction in computer size and increase in its speed create an ongoing effort in search for faster and lower-power transistors. As the intrinsic switching delay of transistors becomes small due to the reduction of the transistor sizes, the interconnection delay begins to dominate the total delay. In highly integrated circuits, the delay-power product $P \cdot \tau$ of transistors can be expressed by $P \cdot \tau \simeq C_L \cdot (\Delta V)^2$, with C_L being a load capacitance and ΔV a logic swing. In these circuits, the reduction of the logic swing turns out to be quite important to obtain better performance.

Josephson junction devices have high-speed and low-power switching characteristics due to their extremely small logic swing of a few mV. Superconducting interconnection lines with zero electrical resistance and distortionless signal transmission characteristics can be also utilized in these devices[1]. However, they are essentially two- terminal devices, and it is difficult to obtain a large current gain and input-output isolation in these devices. Thus, the development of superconducting transistors operating with a logic swing of the order of a mV is highly desired.

Considering that impurities in semiconductors have binding energies of the order of 1 to 10 mV, we have proposed a new transistor where an impurity binding energy is utilized as a threshold for a transistor action[2]. We have named this transistor ballistic impurity level transistor (BILT). The transistor operates at low temperature where carrier freeze-out occurs in semiconductors and superconducting interconnection lines are available.

In this paper, the electrical characteristics of a BILT made of Ge with NbN superconducting interconnection lines are studied. It operates with the logic swing of 10 mV, and the voltage drops due to parasitic resistances between the superconductor and the BILT is negligibly small compared to the logic swing. These features imply that integrated circuits with extremely small logic swing can be implemented in BILTs with the aid of superconductors.

2. OPERATION PRINCIPLE OF BILT

A BILT is a unipolar transistor consisting of multiple layers of heavily doped and lightly doped semiconductors with the same polarity.

As the temperature is lowered, carrier freeze-out occurs in the lightly doped semiconductors. On the other hand, heavily doped semiconductors become degenerate and carriers are present even at low temperature.

Degenerate layers in the BILT form the emitter, base, and collector. Freeze-out layers sandwitched by the degenerate layers work as potential barriers for carriers in the degenerate ones. The barrier height is plotted versus the thickness of the freeze-out layer made of Sb-doped Ge in Fig.1. For thick layers, the barrier height are almost independent of the thickness and about the impurity binding energy or a half of it, depending on the degree of impurity compensation[3]. For thin layers, the barrier height decreases with the thickness.

A schematic energy diagram of the BILT in the ON state is shown in Fig.2. A freeze-out layer, F1, located between the base and the collector is designed to be so thick that the barrier height is high enough to prevent the carriers in equilibrium in the base from flowing to the collector. A freeze-out layer, F2, located between the emitter and the base is so thin that the barrier height is low enough for the carriers in the emitter to be injected into the base when the emitter-base voltage is applied. The injected carriers can traverse the base almost ballistically as hot carriers, when the base is sufficiently thin compared to the mean free path. The carriers with the kinetic energies larger than the barrier height of F1 can overcome the barrier and reach the collector. Thus, the collector current flows and the transistor operation of the BILT is possible. The threshold voltage of this transistor corresponds to the barrier height of F1 with the value of around the impurity binding energy. Therefore, it does not depend on fabrication process variations and its uniformity in LSIs is expected to be excellent.

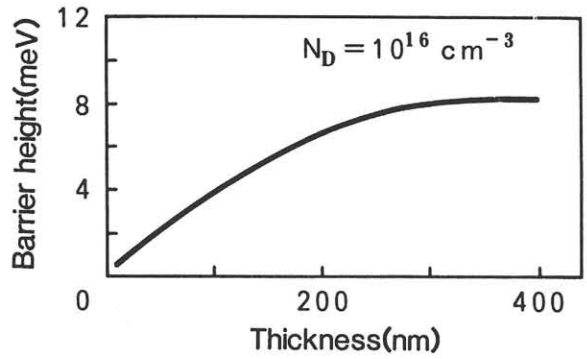

Fig.1. Potential barrier height versus the thickness of a freeze-out layer. The freeze-out layer is made of Sb-doped Ge with the doping density of 10^{16} cm^{-3}.

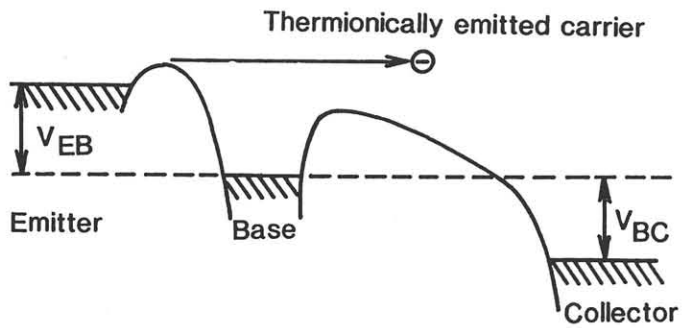

Fig.2. Schematic energy diagram of the BILT in ON state.

3.ELECTRICAL CHARACTERISTICS

The electrical characteristics of a BILT made of Sb-doped Ge are studied theoretically. Impurity binding energy of Sb in Ge is 9.6 meV and the corresponding optimum operating temperature is around 10K. At this temperature, NbN with a superconducting transition temperature of 15K can be used for superconducting interconnection and power lines.

Table 1 shows layer structure of the BILT studied here. In order to obtain a large current gain, the hot carriers have to traverse the thin base almost ballistically. Since the hot carriers have so low kinetic energies of around the impurity binding energy, they are not scattered by the optical phonons. They are scattered mainly by the ionized impurities in the degenerate base.

The ionized-impurity scattering rate τ^{-1} are evaluated using the following screened Coulomb potential with a screening parameter b[4]:

$$\tau^{-1}=\frac{Ne^4m^*k}{2\pi\hbar^3\varepsilon^2}\int_{-1}^{1}\frac{dz}{(2k^2(1-z)+b^2)^2},$$

$$b=(Ne^2/\varepsilon kT)^{1/2}$$

where N is the impurity density, ε the dielectric constant, m* the effective mass, k the wave number of the carriers, T the operating temperature. The typical current gain can be estimated to be 30 using physical parameters shown in Table 1.

The calculated I-V characteristics of the BILT are shown in Fig.3. Here, we have neglected the scattering of hot carriers in the base, to make the calculation simple. The figure shows that the collector current density reaches 2 KA/cm^2 when the emitter-base voltage of 10 mV is applied. Hereafter, we select this operating point for the ON state in the transistor action.

As is used for dopant in the emitter and collector layers to reduce the ohmic contact resistance, because it has a large solubility limit in Ge exceeding 10^{20}cm^{-3}. Ohmic contact resistance per unit area is estimated to be as low as 3×10^{-8} ohm·cm^2 by calculating the tunneling current[3] at a Shottky barrier formed between As-doped Ge and NbN. Here, the Shottky barrier height is assumed to be 0.4 V.

Figure 4 shows a plane view of a BILT studied to evaluate the device performance. The emitter size is assumed to be 1x10 (μm)^2. The voltage drop due to a parasitic resistance in the 500nm-thick collector layer is 0.17mV. The voltage drop at the emitter metal contact is 0.06mV. These voltage drops due to the parasitic resistances are small enough compared to the logic swing of 10 mV to give almost no effect on the transistor action.

Table 2 shows the electrical characteristics

Layer	Material	Thickness
Emitter	10^{20} cm^{-3} As-doped Ge	300 nm
Barrier F2	10^{16} cm^{-3} Sb-doped Ge	150 nm
Base	10^{18} cm^{-3} Sb-doped Ge	25 nm
Barrier F1	10^{16} cm^{-3} Sb-doped Ge	500 nm
Collector	10^{20} cm^{-3} As-doped Ge	500 nm

Table 1. Layer structure of the BILT.

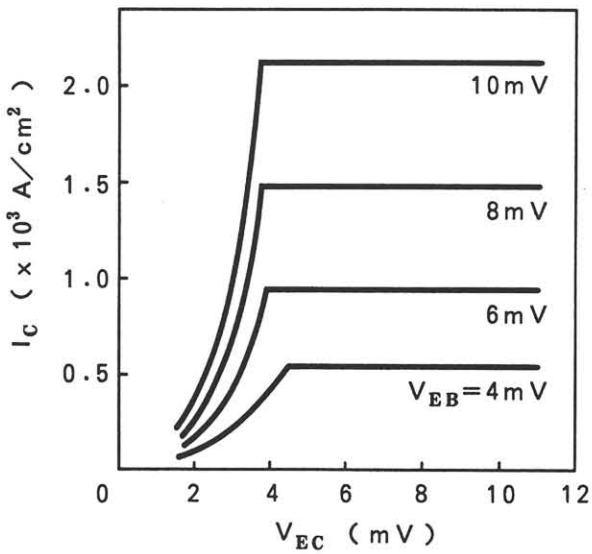

Fig.3. Calculated I-V characteristics of the BILT.

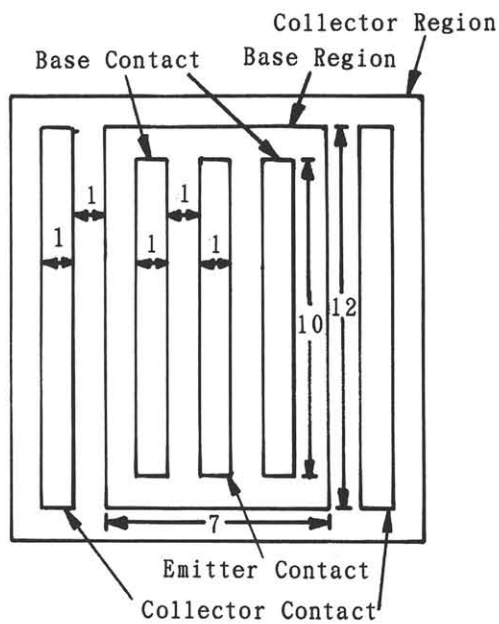

Fig.4. Plane view of the BILT. Sizes are denoted with a unit of μm.

of the BILT. The base transit time τ_b and the collector transit time τ_c are 0.1ps and 1.9ps, respectively. The base resistance R_b is 94 ohm, and the load resistance R_L 50 ohm. Time constant determined by the product of R_b and the collector capacitance C_c is 2.2 ps. Intrinsic switching delay τ_i of the BILT is estimated to be 9.4 ps, using Dumke's expression[5] of,

$$\tau_i = 2.5 R_b C_c + \frac{R_b}{R_L}\tau_b + 3 C_c R_L.$$

Interconnection delay due to a load capacitance is 10 ps/mm, assuming the load capacitance of 200fF/mm. The power dissipated at the transistor in the ON state is as low as 2 μW.

4. CONCLUSIONS

The electrical characteristics of a BILT made of Ge with NbN superconducting interconnection lines have been studied theoretically. The BILT has operated with the logic swing of 10 mV. The voltage drops due to parasitic resistances between the BILT and the superconductor has been small enough to give almost no effect on the transistor action. Extremely small dissipation power and interconnection delay of the BILT have been demonstrated theoretically due to the small logic swing.

Ge molecular beam epitaxial (MBE) growth experiments have been initiated to realize the BILT. So far, Sb-doping and Ga-doping have been successfully achieved in Ge MBE growth[6]. Undope Ge grown by MBE has shown p-type conduction with relatively high carrier density of the order of 10^{16} cm^{-3} at 77K[7], which is not yet low enough to fabricate the BILT.

ACKNOWLEDGEMENT

The author would like to thank Y.Wada for his encouragements during this work.

Logic Swing:	10 mV
Collector Current:	0.2 mA
Collector Current density:	2×10^3 A/cm^2
Specific Contact Resistance:	3×10^{-8} ohm・cm^2
Base Resistance:	94 ohm
Load Resistance:	50 ohm
Emitter-Base Capacitance:	9.5 fF
Base-Collector Capacitance:	24 fF
Load Capacitance:	200 fF/mm
Base Transit Time:	0.1 ps
Collector Transit Time:	1.9 ps
Intrinsic Switching Delay:	9.4 ps
Interconnection Delay:	10 ps/mm
Power Dissipation:	2 μW
Current Gain:	30

Table 2. Electrical characteristics of the BILT.

REFERENCES

1) For example, H. H. Zappe; "Advances in Superconductivity" edited by B. Deaver and John Ruvalds, NATO ASI Series B: Physics 100, p.51.
2) J. Sone; Superlattices and Microstructure 100(1989) 159.
3) S. M. Sze, Physics of Semiconductor Devices, 2nd edition, John Wiley & Sons, Inc.
4) D. Chattopadhyay and H. J.Queisser; Reviews of Modern Phys.53(1981) 745.
5) W. P. Dumke, J. M. Woodall, and V. L. Rideout; State Electron.15(1972) 1339.
6) M. Kawanaka and J. Sone; J. Crystal Growth 95(1989) 421.
7) M. Kawanaka; private communication.