Extended Abstracts of the 1995 International Conference on Solid State Devices and Materials, Osaka, 1995, pp. 186-188

Single Electron Device with Asymmetric Tunnel Barriers

Y.Matsumoto*,T.Hanajiri*,T.Toyabe** and T.Sugano*,***

*Dept.of Electrical and Electronic Eng., **Dept. of Information and Computer Science, Toyo Univ.
2100 Kujirai,Kawagoe,Saitama 350 Japan
***Frontier Research Program RIKEN (The Institute of Physical and Chemical Research)
2-1 Hirosawa,Wako,Saitama 351-01 Japan

Single electron device with asymmetric tunnel barriers (ATBs) is proposed, and its operation has been simulated by computer. The ATB has two remarkable features which cannot be obtained by conventional symmetrical tunnel barrier (STBs). Firstly, the tunnel resistance depends on the energy of tunneling electron and is determined independently of the barrier capacitance. Secondly, the tunneling of electrons becomes almost unilateral rather than bilateral.

1.Introduction

Since single electron transistor (SET) was proposed by Likharev and Averin [1], various circuits based on Coulomb blockade of tunneling have been proposed and demonstrated experimentally[2]. To facilitate the development of practically useful integrated circuits using single electron devices, the operation temperature should be more than 77K and preferably room temperature. However, the operation temperature of conventional single electron devices have remained cryogenic except for the work of Yano *et al.* [3]because of the limitation of current nano- fabrication technology. On the other hand, Lutwyche and Wada[4]have demonstrated that the close correlation between the barrier capacitance and the tunnel resistance makes it quite difficult to operate SET with high speed at room temperature.

Here, single electron device with asymmetric tunnel barriers (ATBs) is proposed in order to overcome this difficulty, and several advantages of ATB over conventional symmetrical tunnel barriers (STBs) are shown.

2. Advantages of ATBs

Basic concept of the ATB is illustrated in Fig.1. An example of ATB can be realized by combining two or more tunnel barriers which have different barrier heights as shown in Fig.1(a).

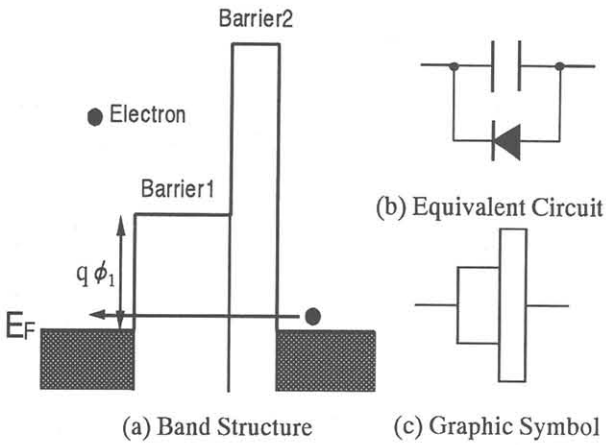

Fig.1 Band structure of ATB at zero bias voltage, equivalent circuit and graphic symbol.

The band structures with various bias voltages are shown in Fig.2.

As shown in Fig.2(a), when a barrier voltage is lower than ϕ_1, electrons tunnel through both the barrier 1 and the barrier 2 successively. Consequently the tunnel resistance of the junction is the sum of R_1 and R_2 and the barrier capacitance is also the series connection of C_1 and C_2.

On the other hand, as shown in Fig.2(b), when a barrier voltage is higher than ϕ_1, electrons tunnel through only the barrier 2 and then electrons are immediately relaxed to the Fermi level of the metal island in less than 10^{-14} sec. On the other hand, the barrier capacitance is the series capacitance of C_1 and C_2, while the tunnel resistance is only R_2, that is, tunnel resistance is determined by high energy electrons and the capacitance is determined by low energy electrons which are induced at opposite side of the barriers.

As shown in Fig.2(c), when positive voltage is applied to the left-hand side of the barrier, electrons tunnel through both the barrier 1 and the barrier 2. Consequently, the tunnel resistance of the barrier is always the sum of R_1 and R_2, and the barrier capacitance is the series connection of C_1 and C_2. Therefore, the current-voltage characteristics of ATB becomes asymmetrical.

The principal points of remarkable features of ATB are summarized as follows.

(1) The tunnel resistance is a function of the energy of tunneling electron.
(2) The lower barrier height determines the threshold of easy current flow.
(3) The barrier capacitance is always determined by the total thickness of ATB even if electrons tunnel through only one barrier.
(4) Asymmetric band structure makes asymmetric current-voltage characteristics.

These features cannot be obtained by STB. When ATBs are used to build single electron devices, the lowering of the tunnel resistance without increasing the barrier capacitance becomes possible and the room temperature operation of SET with high switching speed will be realized more easily than that of STB SETs. In addition, high on-off ratio in barrier resistance is obtained by ATB.

3. Current-voltage characteristics of SET with ATBs

Figure 3 shows the gate voltage (V_g)- the drain current (I_d)

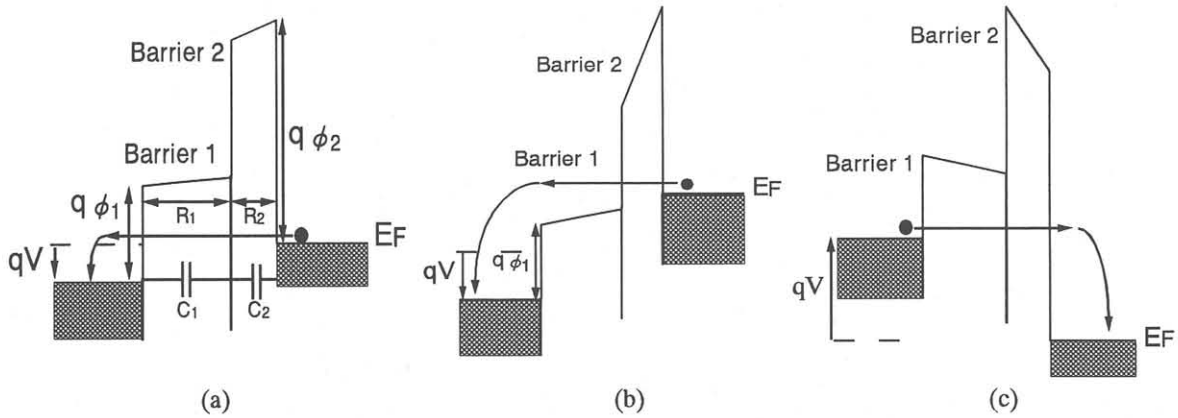

Fig.2 Band structure; (a) with a positive voltage (V< ϕ_2) (b): with a positive voltage (V> ϕ_2) (c): with a negative voltage. The voltage indicated in each caption is that of the left hand side electrode with reference to that of the right hand side electrode.

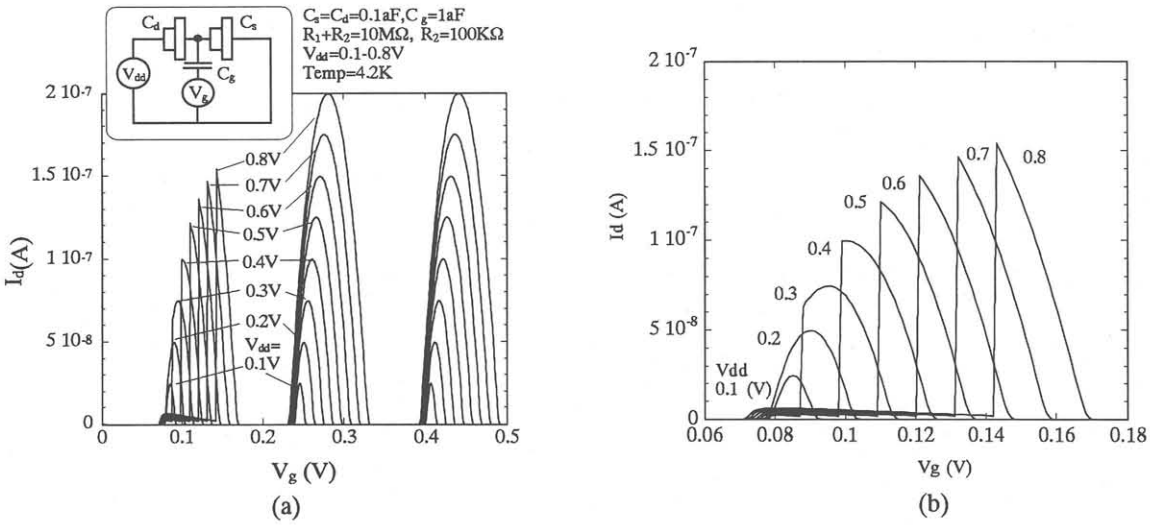

Fig.3 V_g-I_d characteristics of basic SET circuit. The parameter is V_{dd}. The lower barrier height of source and drain ϕ_1 is 30meV.

characteristics of a basic single electron transistor (SET)s circuit calculated by solving the rate equations. The circuit of SET and its circuit parameters are shown in the insertion of the figure. When V_g is below 0.2 V, I_d increases abruptly as V_{dd} increase as shown in Fig.3(b) . This means that the tunnel resistance changes from R_1+R_2 to R_2 and this part is controlled by changing the barrier height of barrier 1. When V_g is above 0.2V as shown in Fig.3(a), the barrier voltage is always higher than ϕ_1 and the value of I_d shows the same value as that when the tunnel resistance is R_2.

Figure 4 shows V_{dd}-I_d characteristics of ATB. When a positive voltage is applied to ATB, large tunnel current flows. On the other hand, negative voltage is applied to the source ATB, tunnel current is the same value as that of STB. Namely, the forward tunneling current is larger than backward tunneling current. This result indicates that tunneling current becomes more likely to be unilateral. Therefore, the equivalent circuit of ATB is expressed by a semiconductor diode and a capacitance as shown in Fig.1(b).

This directionality of tunneling current makes it possible to improve the transfer accuracy of single electron devices,

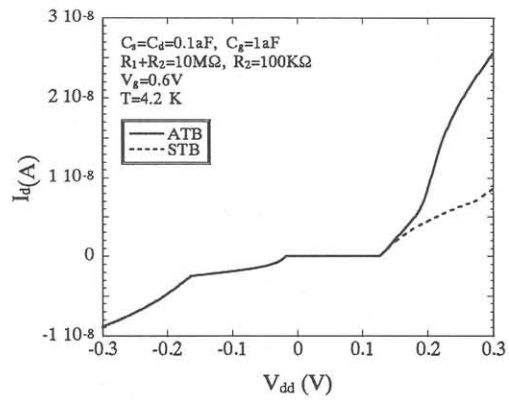

Fig. 4 V_{dd}-I_d characteristics of basic SET circuit. The circuit parameters are shown in Fig.3.

especially when the ATB is applied to turnstile, pump or other multiple tunnel junction systems.

The time constant of the barrier determined by RC is controlled by a bias voltage: when the period of signal cycle is shorter than the time constant at the forward bias and longer than the time constant at the reverse bias, backward tunneling cannot response to signal cycle and then only forward

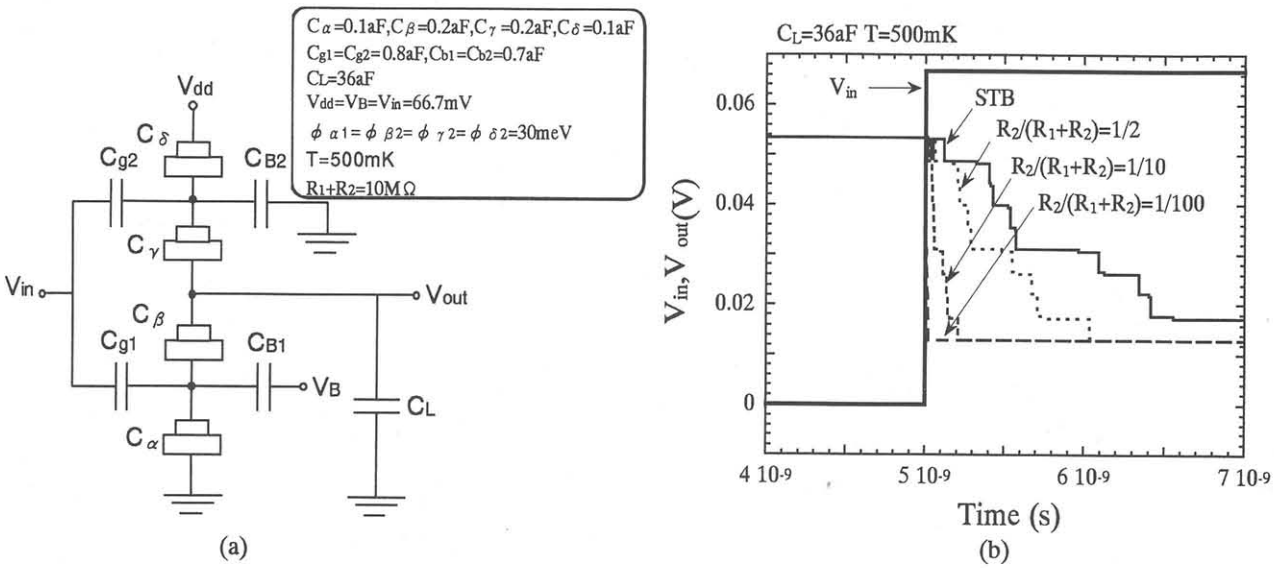

Fig. 5 Configuration of a CMOS-like logic circuit and its transient characteristics. Load capacitance and ambient temperature are fixed.

tunneling can occur. As a result, the improvement of transfer accuracy is achieved. Furthermore, this directionality of ATB is expected to make circuit design much simpler.

4. Application to CMOS like logic

One of the applications of this feature to CMOS like logic[5], [6] is shown in Fig.5. Monte Carlo method was used for simulating the performance of this circuit. In this simulation, only R_2 was changed, and the sum of R_1 and R_2 was always chosen to be equal to the tunnel resistance of STB. As shown in Fig.5(b), if the circuit parameters are determined so that the tunnel resistance of the ATB in operation is R_2, the switching speed of the ATB SETs CMOS like circuit increases as the ratio of $R_2/(R_1+R_2)$ decreased with the barrier capacitance fixed.

Figure 6 shows transient characteristics of CMOS like circuit with ATBs for various barrier heights at $T=T_{(limit)}/10$ where $T_{(limit)}$ is 54.7K. As shown in Fig.6, even if the operating temperature is high, the thermal fluctuations can be suppressed by increasing the barrier height.

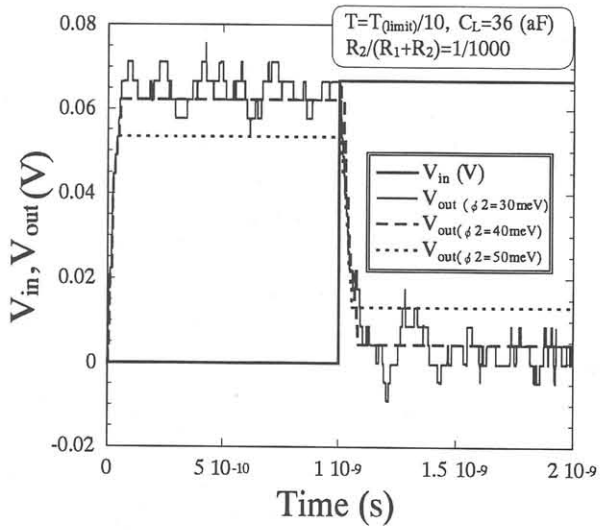

Fig.6 Transient characteristics at various barrier heights at $T=T_{(limit)}/10$.

3.Conclusions

Single electron device with ATBs is proposed and its performance has been simulated. Several advantages of ATB over STB have been found as listed below.

(1)Tunnel resistance is determined independently of the barrier capacitance.

(2)Both high temperature and high speed operation of SETs are realized simultaneously.

(3)High on-off ratio of the barrier resistance is obtained.

(4)Thermal fluctuation in switching behavior is suppressed.

(5)Tunneling current-voltage characteristics becomes asymmetrical.

(6)The accuracy of electron transfer is improved.

These features are expected to facilitate applications of SETs to memory , logic or other circuits.

Acknowledgement

This work is supported by Grant-in-Aid for Scientific Research and Culture #05452200 from the Ministry of Education, Research and Culture of Japan.

References

[1]D.V.Averin and K.K.Likharev, J. Low Temp. Phys. **62**,345 (1985)

[2] see for example, *in "Single charge tunneling"*, ed. by H.Grabert and M.H.Devoret, (Plenum, New York, 1992)

[3]K.Yano,T.Ishii,T.Hasimoto,T.Kobayashi,F,Murai and K,Seki, Ext. Abst.SSDM,325, (1994)

[4]M.I.Lutwyche and Y.Wada, J.Appl.Phys.,**75**, 3654, (1994)

[5] J.R.Tucker, J. Appl. Phys., **72**, 4399, (1992)

[6] M.Kihara, N.Kuwamura, K.Taniguchi and C.Hamaguchi Ext. Abst. SSDM, 328, (1994)