DC Performance of a Tunnel MIS Emitter Auger Transistor

I.V.Grekhov, A.F.Shulekin and M.I.Vexler
194021 St.Petersburg, Russia

Considerable improvement in current gain of a Tunnel MIS Emitter Transistor has been achieved under high base bias condition due to Auger effect initiated by injected hot electrons. DC characteristics of this device have been investigated both theoretically and experimentally. Multistep increase of current gain as a function of base bias, bistable and multistable behavior for common emitter mode operation and some other features arising from Auger effect have been observed.

INTRODUCTION

Tunnel MIS Emitter Transistor (MIS TET) is a promising type of bipolar transistors due to small base width, extremely small base transit time and some other interesting properties. But rather poor current gain obtained in operational devices [1,2,3] was a very serious disadvantage of MIS TET. In this paper we report high current gain MIS TET. Considerable improvement in gain was achieved by application of high base bias \( V_b \) so that the averaged energy of injected electrons exceeded the Auger ionization threshold \( E_g \) for Si. We will use an acronym MIS TEAT (Al-Auger)[4] for our device (Fig.1) since Auger process plays an essential role in this device operation.

We study static characteristics of Al/SiO\(_2\)/n-Si Auger transistor and develop a simple analytical model of this device. Some modifications of TEAT are briefly discussed.

SAMPLE FABRICATION

The transistors whose structure is shown in Fig.1 were fabricated on n-type Si wafer (\( N_a=5.0\times10^{16}\) cm\(^{-3}\)). The p'-contact area was made by boron diffusion to a depth of 2-3 mm. Tunnel-thin oxide (2-3 nm) was formed by oxidation in a stream of dry O\(_2\) at T=700°C. Care has been taken to avoid the tunnel oxide area and heavy doped p'-area being overlapped. Vacuum-evaporated aluminum was used as the electron injector.

ANALYTICAL MODEL OF MIS TEAT

The energy band diagram of MIS TEAT under both base-to-emitter \( V_b \) and collector-to-emitter \( V_c \) bias conditions with a notation used below is shown in Fig.2. The parameters of this diagram may be calculated for the given \( V_b, V_c \) [5] in the same manner as it is done for MIS structures without a charge transport. Of course, Auger ionization effect is important namely at high \( V_b \).

The discrepancies between our model and the analyses of earlier investigators [2,6] restricted by low \( V \) conditions only are following:

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Fig.1. The structure of MIS TEAT.
1) Auger ionization current $j_a$ is regarded. The energy distribution of injected electrons at a Si/SiO$_2$ interface peaks sharply near $E_a = E_F - E_0$. So that all the electrons are assumed to possess an energy $E_a$ just after being injected. But their capability of Auger ionization is determined not only by $E_a$ but also by an additional energy obtained while passing freely:

$$\lambda$$

$$\Delta E = \int P(x) \, dx$$  \hspace{1cm} (1)

$\lambda$ is mean free path, $P(x)$ is electric field in Si. So, Auger generation current is:

$$j_a = \lambda e \cdot \langle P(E_{in} + \Delta E) \rangle$$  \hspace{1cm} (2)

where $j^e$ is electron component of the emitter current (determined as usual [2,6] and $P$ is averaged number of electron-hole pairs produced by one hot electron [7].

2) The formation of a series of 2D subbands at Si/SiO$_2$ interface is taken into account. Supposing that only the ground subband whose bottom we denote as $E$ is occupied by holes we may write for hole leakage into the metal from a discrete level $E_k$:

$$j^h_k = \frac{q}{\hbar} \cdot \frac{2E_k}{N_s \cdot 6(E_0)}$$  \hspace{1cm} (3)

where $N_s$ is a charge density of inversion layer [5], $\theta$ is tunneling probability, $\hbar$ is Planck's constant.

Now, terminal currents are:

$$j_e = j^e + j^h$$  \hspace{1cm} (4A)

$$j_b = j^e + j^e_P + j_d$$  \hspace{1cm} (4B)

$$j_o = j^e_O(1+P) - j_d$$  \hspace{1cm} (4C)

where $j_d$ is hole current from interface into the bulk of Si which is important only in saturation region.

Typical DC characteristics generated on the basis of the present model are in Fig.3. Due to positive feedback arising from Auger effect, the base current $j_b$ slows down and then drops, at sufficiently high $V_{be}$. It means that the differential current gain $\beta_d$ increases and at some $V_{be}$ (in a maximum of $j_o$) for a given $V_{be}$ becomes infinite. Since $j^e$, $j^h$ increases gradually with $V_{be}$, all the features of $\beta_d$, if any, should be attributed to a behavior of actual dependence $P(E_{in} + \Delta E)$, which had been taken in the simplest form [7] for above computation.

**EXPERIMENTAL**

Fig.4 shows the DC characteristics of MIS TEs obtained in operational devices: base current(a), current gain(b), common emitter output characteristics(c).

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**Fig.2. Energy band diagram of MIS TEs.**

**Fig.3. Theoretical DC curves. Parameters: $\chi' = 1.1eV$, $\chi = 2.2eV$, $N_s = 7*10^{10}$ cm$^{-2}$ (2H layer doping), SiO$_2$ thickness 2.5nm, other parameters are the same as in [6], see also [8].**

**Fig.4.** shows the DC characteristics of MIS TEs obtained in operational devices: base current(a), current gain(b), common emitter output characteristics(c).
Multistep increase of current gain $\beta$ as a function of $V_c$ may be attributed to the multistage Auger ionization [4] caused by hot electrons or, in our notation, to the stepwise behavior of $P$. The segments of rapid rise in $\beta$ ($V_c$) are approximately equidistant and the interval between them in $E'/q$. Discontinuities with a change of sign may appear instead of some segments.

In the same range of $V_c$ the base current $J_b (V_c)$ slows down or even drops. An interrelation between the anomalies in $\beta$, $J_b (V_c)$ and $J_e (V_c)$ which is clearly seen in Fig.4 may be easily demonstrated using our analytical model.

Output characteristics of Auger transistor exhibit $S$-shape segments. The number of these segments is normally equal to the number of segments of a drop in $J_e (V_c)$ curve.

The characteristics similar to those shown in Fig.4 were observed in all studies of the transistor over a wide range of insulator thickness.

**Modifications of TEAT**

Possible modifications of TEAT are Auger transistor with a doped $p^-$-base underneath the tunnel insulator and metal base transistor (Fig.5a,b). TEAT with a doped base was fabricated but found to exhibit lower gain than the device with an induced base shown in Fig.1, because of recombination effect in the base. For this reason, fabricating TEATs with an induced base we tried to avoid the thin oxide and $p^-$-areas being overlapped. Such an overlap could result in a decrease of $\beta$ since it means that TEATs shown in Figs.1,5a,b are connected in parallel. The advantages of the structures with a doped, metal or superconducting base vis-a-vis the device with an induced base are smaller lateral resistance or the base.

**Conclusion**

Summarizing the results obtained in this paper we may conclude that, due to Auger effect, MIS TEAT is a much more promising device than the devices of this type studied earlier.

**References**