Extended Abstracts of the 21st Conference on Solid State Devices and Materials, Tokyo, 1989, pp. 361-364

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# Analysis of a $\mu$c-Si Hetero-emitter Transistor by Changing Operation Temperature

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ABSTRACT

Temperature dependences of collector, base current and current gain of a $\mu$c-Si hetero-emitter bipolar transistor have been measured and analyzed. Collector current anomaly is observed, and explained by warm electrons induced in the emitter region. Base current shows insensitive characteristics to temperature. A tunneling process is considered for this reason. Under these condition, current gain shows positive, not always negative, temperature coefficient.

## 1. INTRODUCTION

In the electrical characteristics of the bipolar transistor, there are various temperature factors related to the injection-, transport- and recombination-process of carriers. Thus, discussions on temperature dependence of devices can be said a useful method for us to understand the operation mechanism. Moreover, low temperature operation of bipolar transistors including heterojunction bipolar transistors (HBTs) will come significant to realize future cooled Bi-CMOS devices.

Although there have been many reports concerning with temperature dependence on Si homojunction transistors[1], a temperature dependence of only current gain for Si-HBT has been investigated[2].

In order to make clear the behavior of the device mechanism of the Si-HBT at low temperature, we have measured the collector, base current and current gain of a microcrystalline silicon($\mu$c-Si) hetero-emitter transistor by changing operation temperature. In this paper, collector current anomaly will be discussed. Also behavior of a base current and a current gain will be presented.

## 2. EXPERIMENTS

Conventional Si IC process was used to fabricate the HBT. Details of the fabrication procedure, the structure of the HBT and preparation conditions of $\mu$c-Si films for making a hetero-emitter are written in elsewhere[3].

A Si-HBT chip was set in a vacuum cryostat system. A thermocouple (C.A., 100$\mu$m$\phi$) was directly attached near the device in order to measure the device temperature accurately. Collector and base currents were measured in the temperature range from 293 K to 186 K as a function of base-emitter applied voltage in the common emitter configuration by using HP 4145B parameter analyzer. Emitter-Collector applied voltage was set at 5V to prevent the device from saturation operation. In this measurements, the device used has current gain of about 300 at room temperature. The emitter dimension is 20x80$\mu m^2$.

## 3. RESULTS AND DISCUSSION

### 3.1 Collector Current

According to the simple carrier diffusion model, collector current $I_C$ should obey the following relationship,

$$I_C = I_{C0} \exp(qV_{BE}/nkT) \qquad (1)$$

where, q: the electronic charge, $V_{BE}$: the base-emitter applied voltage, n: the non-ideality factor, k: the Bolztmann's constant, T: the absolute temperature, $I_{C0}$: the saturation current of collector current.

Relations measured between the collector current and the base-emitter applied voltage are shown in Fig. 1. In this figure, the dashed line shows a collector current calculated by using eq. (1). Here, $I_{C0}$ is roughly calculated as shown in the figure caption. It can be found that these results have differences with eq. (1) on several points.

First of all, a larger collector current than the theoretical value is observed.

Secondly, in spite that the n-value for collector current must be unity since collector current consists of a diffusion current, n-values determined from Fig. 1 show to have ones around 1.3 as shown in Fig. 2.

In order to investigate $I_{C0}$ in more detail, Arrhenius plots are performed, and shown in Fig. 3. As can be seen in this figure, the plots are fitting on a line very well over 10 decades. Where we plot $I_{C0}/T^m$

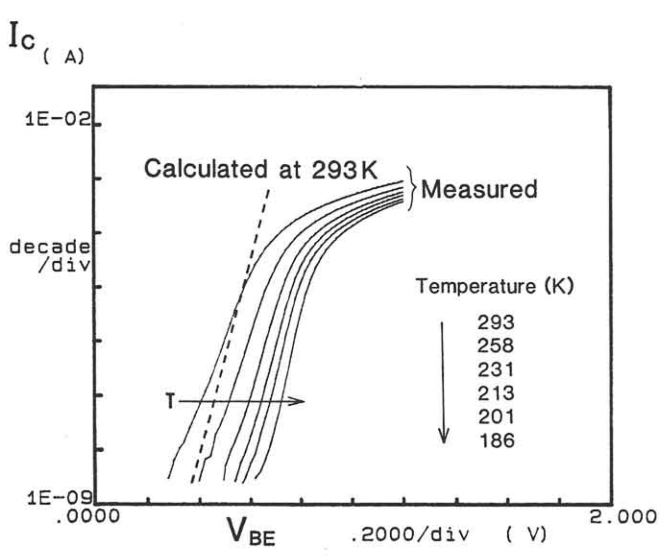


Fig. 1
Temperature dependence of collector current. $I_{C0}$ ($=1.4\times10^{-15}$ A) is calculated by using $I_{C0}=A_E q n_i^2 D n_B / \int N_{AB}\,dx$,
where we use $A_E=1.6\times10^{-5}$ cm$^2$, $q=1.6\times10^{-19}$ C, $n_i=1.5\times10^{10}$ cm$^{-3}$, $Dn_B=20$ cm$^2$/s, $\int N_{AB}\,dx=8\times10^{12}$ cm$^{-2}$.

instead of $I_{C0}$ for the vertical axis, considering contributions of temperature dependence for effective density of states and diffusion coefficient of electrons. The influence of m on the derived value is shown in the inset of Fig. 3. As shown in this figure, even though m varies from 0 to 3, the apparent

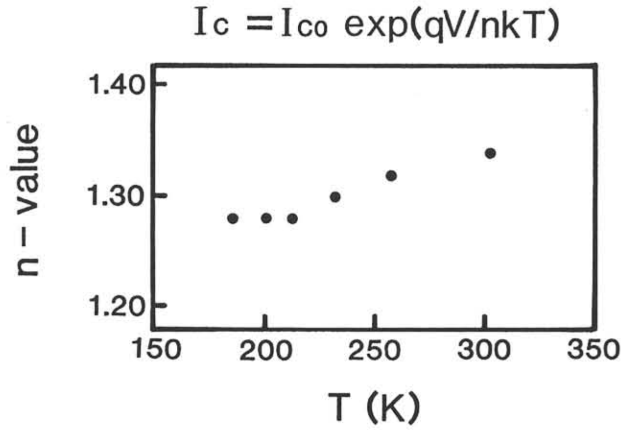


Fig. 2
Temperature dependence of n-value derived from collector current.

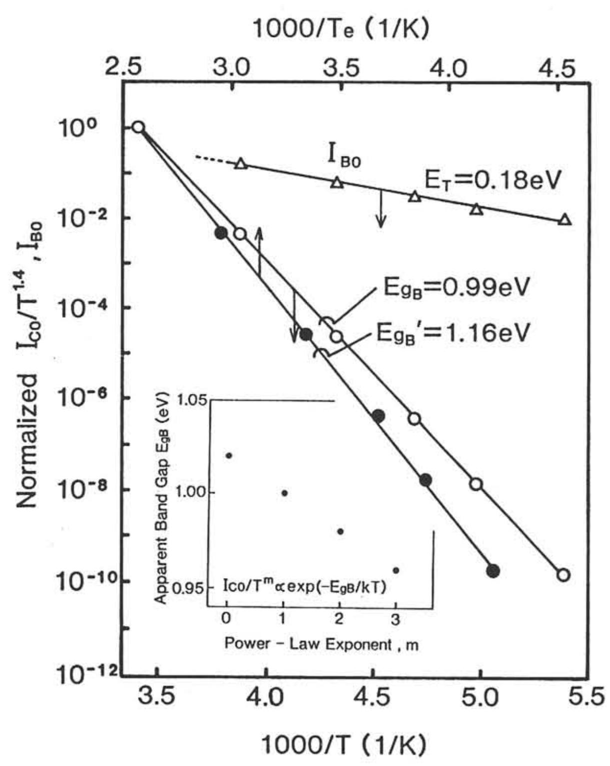


Fig. 3
Arrhenius plots of $I_{C0}/T^{1.4}$ and $I_{B0}$ and contribution of factor m to $E_{gB}$.

band gap $Eg_B$ dose not exceed 1.02 eV and the error is within only 6%. Therefore, we can conclude that there is only a little contribution of the factor m of $T^m$ to $Eg_B$.

Since this activation energy has been derived from temperature dependence of excess carriers flowing into the base region, this value should be the value of the energy gap of cyrstalline Si-base region. However, the activation energy is determined to be 0.99eV, where we have chosen m=1.4 after the reference[1]. This value is obviously smaller than the band gap of Si.

An explanation for above discrepancies could be given by simple mismeasurement of the temperature and device heating. However, considering that 100℃ higher temperature than room temperature is necessary to make the n-value unity, and that the collector current region defining n-values is as small as 1 $\mu$A order, the discrepancies could not be explained by such explanations.

Band gap narrowing of the base might be a reason to explain the larger collector current. However, because the base is doped by only an order of $10^{17}$ $cm^{-3}$, this value is not so high as to bring the base into band gap narrowing.

For the characteristics that apparent n-values exceed unity, other explanations using a potential spike at a heterojunction[4] and an insulating layer between emitter and base[5] are reported. In such cases, collector current shows a smaller value than ideal diffusion current. Therefore, such explanations can not be applicable to our case because collector current shows larger value than the theoretical diffusion current.

In order to explain the characteristics, we assume the effective temperature so as to make n-value unity. Then, $I_{C0}$ is plotted by using this temperature as shown in Fig.3. As can be seen in this figure, plots are well fitting on a straight line, and an activation energy of $Eg_B'$ is determined as 1.16 eV. This value is close to the reported value of about 1.2 eV for a homojunction transistor[1].

This fact might mean that the measured temperature or the lattice temperature of Si differs from the effective electron temperature in the device. In other words, electrons become "warm". A plausible explanation could be made as follows.

An electric field might be induced in a neutral region of the $\mu$c-Si emitter due to its resistance. Then, electrons will be accelerated and get excess energy beyond thermal equilibrium. As the result, electrons might become warm. According to the above analysis, the equivalent temperature for electrons Te is denoted by n・T. In other words, the ratio Te/T is equal to n-value(~1.3), and this value almost constant.

## 3.2 Base Current

Slope of the base current $I_B$ is observed as constant independently of temperature as shown in Fig.4. This kind of current could be explained by a tunneling process and base current can be expressed as follows,

$$I_B = I_{B0}\exp(\xi V_{BE}) \qquad (2)$$

where $\xi$ is the parameter determined by tunneling barrier and is independent of tempera-

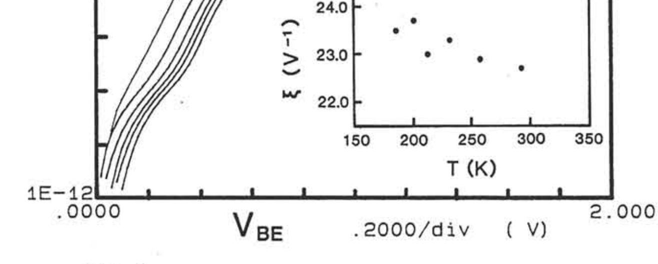


Fig.4
Temperature dependence of base current and parameter $\xi$.

ture. As shown in Fig.4, $\xi$ shows constant value of around 23 $V^{-1}$. The activation energy $E_T$ determined by base saturation current $I_{B0}$ shows as small as 0.18 eV as shown in Fig.3. These mean that base current of this HBT dose not consist of a diffusion current, nor a recombination current. Then we could say that a reverse injection is suppressed by a wide band gap hetero-emitter effect.

Furthermore interesting behavior of base current can be found in Fig.4. The base current shows a positive temperature coefficient in the region of $V_{BE}<1V$. However, in the region of $V_{BE}>1V$, temperature coefficient shows negative. From this result, it is considered that base current transport mechanism changes across $V_{BE}=1V$.

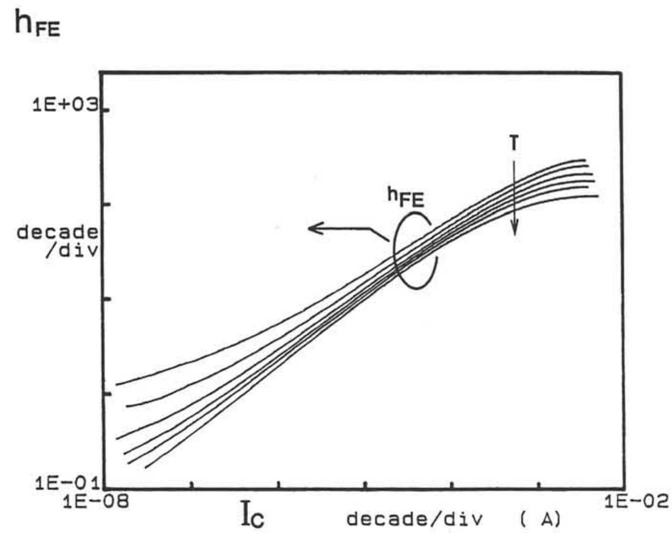


Fig.5
Temperature dependence of current gain $h_{FE}$.

3.3 Current Gain

In ideal HBT, current gain is governed by transport factor in the base region. Therefore, it is considered that temperature dependence of current gain is determined by temperature dependence of a diffusion constant of electrons in the base region. Its temperature coefficient generally shows weak negative characteristics. In this HBT case, positive temperature coefficient of the current gain is observed as shown in Fig.5. It is considered that the reason of this is due to non-ideal base current.

## 4. CONCLUSION

Characteristics of Si-HBT with a $\mu$c-Si hetero-emitter are analyzed by changing operation temperature. Comparing with a homojunction transistor and low resistance emitter HBT, complicated and non-ideal behavior such as warm electron for collector current and tunnel current for base current were observed. At least, it is noted that current gain shows positive temperature coefficient, not always negative, under such conditions.

## ACKNOWLEDGMENT

The authors are wish to thank Mr. T.Fukazawa at Nippon Denso for useful discussion and measurements.

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