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A New Si Bipolar Transistor Using Amorphous SiC:H as a Wide-Gap Emitter

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A new Si heterojunction bipolar transistor using amorphous SiC:H as a wide band gap emitter has been investigated. Satisfactory transistor operation was clearly observed with common emitter current gain of around 50 at a current density of 2.4 A/cm^2 in a pnp specimen. An enhanced current gain of 70 was achieved in a preliminary npn sample with a base concentration about four times than that of the pnp specimen. For the same Gummel number, the gain obtained in the npn sample is about 20 times greater than that in the pnp specimen.

1. Introduction

Recently, several new emitter materials for bipolar transistors , such as SIPOS[1], poly-Si[2] and a-Si:H[3], are being considered in Si field which don't involve epitaxial technology. Current gains larger than that obtained in a homojunction transistor were achieved in these heterojunction bipolar transistors (HBT). Especially, an amorphous emitter is promising because of 1) low temperature process, 2) easy and inexpensive fabrication and 3) wider band gap than the crystalline material. It is worthwhile to note that successful application of amorphous semiconductor material as the active region of three terminal devices has been hardly achieved until now.

Presently, Bi-CMOS technology, which combines the merits of low power dissipation of CMOS devices with the high current drivability of bipolar transistors, is being developed. In this perspective, an amorphous emitter HBT is attractive because it involves low temperature and easy fabrication thus offering good compatibility with Bi-CMOS process.

In this paper, we explain and discuss on the characteristics, mechanism of current transport and the energy band diagram of an a-SiC:H (emitter)/c-Si(base, collector) HBT realized for the first time.

2. Experimental procedure

Conventional Si process was used for transistor fabrication. Figure 1 illustrates the fabrication steps.

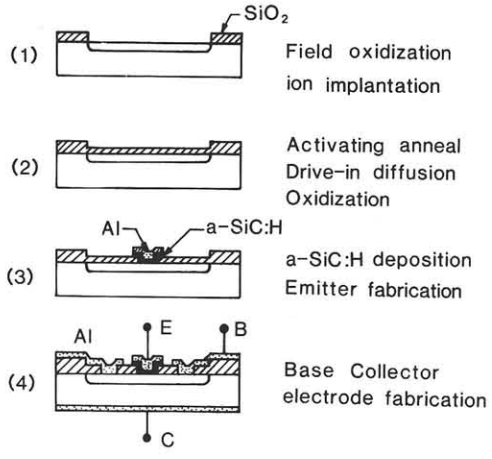

Fig. 1. Schematic diagrams of steps of the fabrication process and the cross section of transistor.

1) A field oxide film (thickness = 0.5 μm) was first grown thermally (1000 °C, 100 min, wet) on a chemically precleaned Si substrate. A window was cut into it and ions were implanted through this window to form the base region.

2) A second oxidation (1025 °C, 30 min, wet; oxide thickness ≃ 0.2 μm) was carried out to bring about base drive-in diffusion, activation

of the implanted impurities and passivation of the base surface, simultaneously.

3) An emitter window (area = 4.18×10^{-4} cm^2) was cut into the oxide, the base surface was cleaned (boiled in HNO_3 and RCA solution for 10 min each, followed by HF dip) and the substrate was loaded into the discharge chamber of an inductive coupled plasma assisted CVD system wherein a-SiC:H was deposited on the whole surface. Al emitter electrode was then fabricated and using this as mask, plasma etching using CF_4 gas was carried out to etch out the a-SiC:H film.

4) Finally, the base and collector electrodes were formed.

Different conditions related to the fabrication process appears in Table 1.

		Transistor type	
		pnp	npn
Si substrates	Resistivity (Ωcm)	3~5 p type	7 n type
	Orientation	(1 1 1)	
Base ion implantation	Ion	P^+	B^+
	Dose (cm^{-2})	2×10^{12}	8×10^{12}
	Energy (keV)	160	50
a-SiC:H deposition	Gases	$SiH_4 : CH_4 = 0.8 : 0.2$	
	Doping gases	B_2H_6(15%)	PH_3 (3%)
	Substrate temperature (°C)	450	350
	Film thickness (nm)	60	100

Table 1. Fabrication conditions for pnp and npn HBTs.

3. Results and discussion

The curve-tracer common emitter V_{CE}-I_C characteristics of the pnp transistor at room temperature is shown in Fig. 2. Satisfactory transistor operation is clearly observed with common emitter current gain $h_{FE(max)}$ of 50 at a current density of 2.4 A/cm^2. Early effect can be observed in these characteristics since the base impurity concentration is relatively low. The loops that are observed at the lower voltage range disappeared when H_2 plasma anneal was carried out for

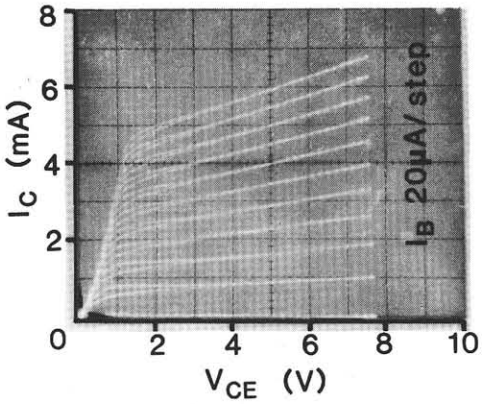

Fig. 2. Curve tracer presentation of the transistor common emitter I_C - V_{CE} characteristics.

30 min at 300 °C[4]. Furthermore, no significant variation of current gain was observed when H_2 plasma anneal was carried out for as long as 3.5 hours. Adverse results were reported for SIPOS and a-Si:H HBTs[1),3)].

The h_{FE}-I_C and emitter-base junction forward I-V characteristics at various temperatures were investigated in order to estimate the band structure and the current transport mechanism of the HBT. No current gain decrease was observed in the lower current range of 10^{-6} -10^{-4} A. The 'n' value of the emitter-base junction was as good as 1.1 - 1.3.

Arrhenius plots of J_0, the emitter-base junction saturation current that has been obtained by extrapolating the forward I-V characteristics, and that of h_{FE} appears in Fig. 3. These logarithmic plots show a straight line behaviour.

An energy band structure, as shown in Fig. 4, is suggested for the a-SiC:H/c-Si heterostructure under the assumptions that:

1) The electron affinity of a-SiC:H is close to that of c-Si as a consequence of which the valence band discontonuity turns out to be greater than that for the conduction band, and

2) the built-in voltage appears mainly on the a-SiC:H side of the junction.

Considering the difference between the barriers for electrons, V_n and that for holes, V_p to

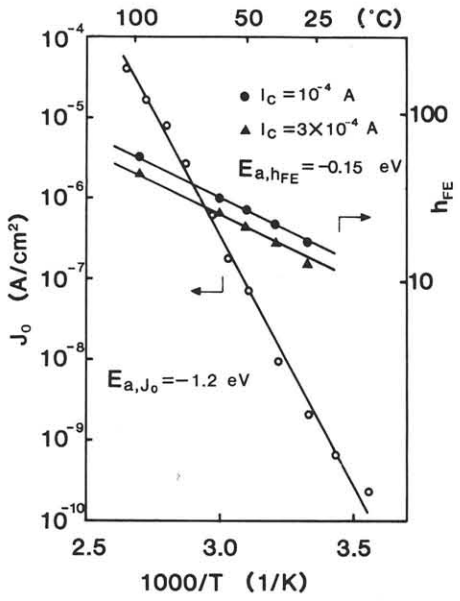

Fig. 3. Temperature dependence of h_{FE} and diode saturation current, J_0.

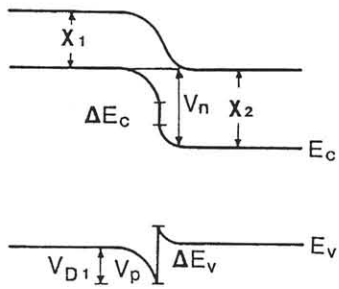

Fig. 4. Suggested energy band structure of the a-SiC:H/c-Si heterojunction.

be approximately equal to ΔE_C, it can be said that h_{FE} in this structure is larger than in a homojunction transistor by a multiplication factor $\exp(\Delta E_C/kT)$[5].

On the other hand, since amorphous semiconductor possesses fairly deep carrier activation energy, $E_{a,\sigma}$, the amorphous emitter concentration and therefore h_{FE} increases as a function of $\exp(-E_{a,\sigma}/kT)$.

Considering the above two factors and neglecting the temperature dependence of base transport factor, the temperature dependence of h_{FE} can be expressed as:

$$h_{FE} \propto \exp(E_{a,h_{FE}}/kT) \qquad (1)$$

where,

$$E_{a,h_{FE}} = \Delta E_C - E_{a,\sigma} \qquad (2)$$

Substituting the value for $E_{a,h_{FE}} = -0.15$ eV, obtained from Fig. 3 and that for $E_{a,\sigma} = 0.28$ eV[6], obtained from a σ - 1/T plot, into Eq. (3), $\Delta E_C = 0.13$ eV is obtained:

$$\Delta E_C = E_{a,h_{FE}} + E_{a,\sigma} = 0.13 \text{ eV} \qquad (3)$$

Similarly, $\Delta E_V = 0.57$ eV is obtained by substituting the values of $E_{g1(opt)} = 1.8$ eV[6], $E_{g2} = 1.1$ eV and that of $\Delta E_C = 0.57$ from Eq.(3) into Eq. (4) as follows:

$$\Delta E_V = E_{g1(opt)} - E_{g2} - \Delta E_C = 0.57 \text{ eV} \qquad (4)$$

The saturation current, J_0 in the heterojunction may be expressed by[7]:

$$J_0 = q\chi N_A (D_p/\tau_p)^{1/2} \exp(-qV_{D1}/kT) \qquad (5)$$

where, q = unit electronic charge, χ = transport factor, N_A = hole concentration of a-SiC:H, D_p, τ_p = diffusion constant and lifetime, respectively, of minority carriers in the base region and V_{D1} = the built-in voltage on the a-SiC:H side.

Considering the temperature dependence of N_A as discussed above, the temperature dependence of J_0 can be expressed as follows:

$$J_0 \propto \exp(E_{a,J_0}/kT) \qquad (6)$$

and,

$$E_{a,J_0} = -(E_{a,\sigma} + qV_{D1}) \qquad (7)$$

Substituting values for $E_{a,J_0} = -1.2$ eV obtained from Fig. 5, the value for qV_{D1} can be estimated to be:

$$qV_{D1} = -E_{a,\sigma} - E_{a,J_0} = 0.92 \text{ eV} \qquad (8)$$

Since the built-in voltage derived from C-V characteristics was found to be about 0.9 eV[6], this justifies the assumption made for the present model.

A band strcture for the pnp HBT, based on the above results, appear in Fig. 5(a). The band profile for a npn structure can be derived from this figure and is as shown in Fig. 5(b).

The reason why the current gain obtained in the pnp HBT is not so high is because of a rather low barrier energy for electrons, ΔE_C. However, in the npn structure, the barrier energy for holes, ΔE_V is much higher which suggests that a higher gain is attainable in the npn structure. The current gains of pnp and npn HBTs are shown in Fig. 6 for several Gummel numbers. Actually, a preliminary npn sample gave a gain of 70 which is 20 times larger than in the pnp structure for the same Gummel number.

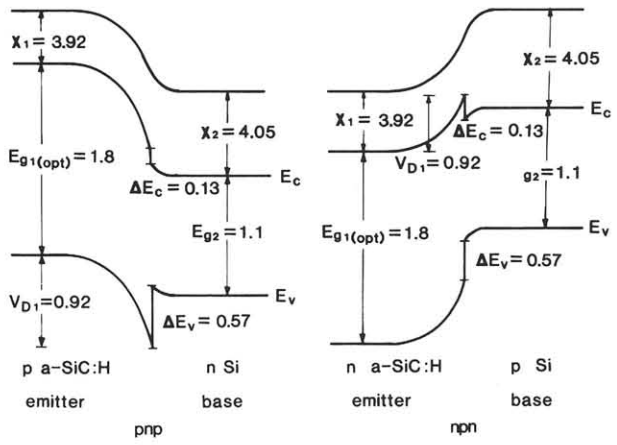

Fig. 5. (a) Estimated energy band diagram of the pn a-SiC:H/c-Si heterojunction.
(b) The same expected for a np structure.

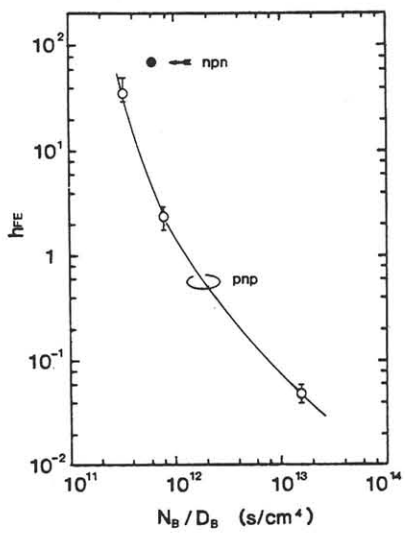

Fig. 6. Experimental values of h_{FE} for pnp and npn HBTs as a function of Gummel number.

4. Summary

1) An a-SiC:H emitter pnp HBT with a current gain of 50 at a current density of 2.4 A/cm^2 has been realized.
2) The band structure of the pnp HBT was estimated from the temperature dependence of h_{FE} and emitter-base junction saturation current, J_0.
3) The conduction and valence band discontinuities in this band structure was calculated to be 0.13 eV and 0.57 eV, respectively, suggesting that a npn structure would give a higher h_{FE}.
4) A npn HBT was fabricated and preliminary results gave a current gain of 70 at a current density of 0.72 A/cm^2. This is a value 20 times of that obtained for the pnp one for the same Gummel number.
5) The npn results confirm the validity of our qualitative speculation regarding the difference in barriers for holes and electrons in the pnp and npn structures.

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