Measurement of the bandgap narrowing in the base of Si homojunction and Si/Si_{1-x}Ge_x heterojunction bipolar transistors from the temperature dependence of the collector current

P. Ashburn, A. Nouailhat* and A. Chantre*

Dept. of Electronics & Computer Science, University of Southampton, S09 5NH, U.K.

** CNET-CNS, France Telecom, BP. 98, 38243 Meylan, France*

Abstract: A method is described for measuring the bandgap narrowing in the base of a Si homojunction or Si/SiGe heterojunction bipolar transistor from the temperature dependence of the collector current. The model includes the temperature dependence of the intrinsic carrier concentration, the bandgap, the minority carrier mobility, and freeze-out of dopant in the base. The analysis method is applied to transistors with epitaxial Si and SiGe bases, and also to Si devices with ion implanted bases. For the epitaxial base transistors, where the base boron profiles are sharp, a linear characteristic is obtained from which the bandgap narrowing in the base can be calculated. For a SiGe HBT with 16% Ge in the base, a bandgap narrowing of 117meV is obtained, which compares very well with the theoretical value of 117meV for the valence band offset. For the implanted base transistors, a linear characteristic is not obtained. This is explained by the presence of doping tails on the base profile.

1. Introduction

The low temperature operation of Si bipolar transistors (BJTs) and Si/Si_{1-x}Ge_x HBTs is of interest for BiCMOS circuit operation at liquid nitrogen temperature. The major obstacle to the successful realisation of cryogenic BiCMOS circuits is the low gains which are often obtained in bipolar transistors at low temperatures. The device parameter which has the biggest impact on the low temperature current gain is the bandgap narrowing in the base compared with that in the emitter. In this paper, a new method is described for measuring the bandgap narrowing in the base of a Si BJT or a Si/Si_{1-x}Ge_x HBT from the temperature dependence of the collector current. This method is tested on transistors with uniformly doped epitaxial Si and Si_{1-x}Ge_x bases and on Si transistors with ion implanted bases.

2. Theory

The collector current of a homojunction bipolar transistor can be written as:

$$I_C(T) = \frac{qAD_n(T)n_i^2(T)}{W_B N_A(T)} \exp \frac{qV_{BE}}{kT} \exp \frac{\Delta E_{GB}}{kT} \quad (1)$$

where $D_n(T)$ is the minority carrier electron diffusivity in the base, $n_i(T)$ the intrinsic carrier

concentration, $N_A(T)$ the doping concentration in the base, which is assumed to be uniform, and ΔE_{GB} the doping-induced bandgap narrowing in the base. The other terms have their usual meanings. The temperature dependence of the electron diffusivity is given by the Einstein equation and the intrinsic carrier concentration by:

$$n_i^2(T) = T^3 \exp \frac{-E_G(T)}{kT} \quad (2)$$

where $E_G(T)$ is the silicon bandgap. In this work, the temperature dependence of the bandgap is described using the expression of Thurmond [1]. Freeze-out of dopant in the base is measured from the temperature dependence of the intrinsic base sheet resistance:

$$R_B(T) = \frac{1}{qW_B\mu_p(T)N_A(T)} \quad (3)$$

where $\mu_p(T)$ is the majority carrier hole mobility in the base. Combining equations (1) to (3) then gives:

$$I_C(T) = C_C T^4 \mu_n(T) \mu_p(T) R_B(T) \exp \frac{qV_{BE} - E_G(T)}{kT} \exp \frac{\Delta E_{GB}}{kT} \quad (4)$$

The temperature dependences of the majority and minority carrier mobilities are assumed to be the same, and are described using the model of Arora [2]. Equation (4) can be used to extract a value for ΔE_{GB} from the measured temperature dependence of the collector current. A similar method can also be used to determine the total bandgap narrowing in the base in $\text{Si/Si}_{1-x}\text{Ge}_x$ heterojunction bipolar transistors. In this case however, the bandgap narrowing has two components, one due to the boron doping and one due to the germanium.

3. Results

Fig.1 shows 306K and 116K Gummel plots for a homojunction bipolar transistor (BJT)

Figure 1 Gummel plots at 306 and 117K for an epitaxial base BJT

Figure 2 Gummel plots at 306 and 116K for a $\text{Si/Si}_{1-x}\text{Ge}_x$ HBT

with a $6 \times 10^{18} \text{cm}^{-3}$ epitaxial base and fig.2 plots for a comparable $\text{Si}/\text{Si}_{0.84}\text{Ge}_{0.16}$ HBT. The collector characteristics of both devices are ideal, and hence can be reliably used to extract the bandgap narrowing in the base. At 306K, the collector current of the HBT is a factor of 70 larger than that of the BJT, but this increases to a factor of 80,000 at 116K. As a result, the gain of the HBT increases with decreasing temperature, leading to a value of about 600 at 116K. This is more than adequate for successful circuit operation at liquid nitrogen temperature.

Fig.3 shows the temperature dependence of the intrinsic base sheet resistance for the homojunction and heterojunction bipolar transistors. The sheet resistance of the BJT is lower than that of the HBT at all temperatures. SIMS measurements show that this is due to a wider base in the case of the BJT. The increase in sheet resistance at high temperatures is due to the temperature dependence of the majority carrier hole mobility. The constant values of sheet resistance at low temperatures indicate that there is little freeze-out of boron in the base of either device. Values of mean base doping concentration can be calculated from the measured base sheet resistances and basewidths (from SIMS), and were found to be $6 \times 10^{18} \text{cm}^{-3}$ for both the BJT and HBT.

Figure 3 Intrinsic base sheet resistance as a function of reciprocal temperature for a Si BJT and a $\text{Si}/\text{Si}_{0.84}\text{Ge}_{0.16}$ HBT

The bandgap narrowing in the base of the BJT can be obtained by plotting equation (4) as shown in fig.4. The activation energy of 44meV represents the bandgap narrowing in the base due to heavy doping effects, and can be compared with a theoretical value of 54meV from the bandgap narrowing model of Klaassen [3] or 75meV from the model of Swirhun [4]. A similar approach can be used for the HBT, as again shown in fig.4. Here the activation energy of 161meV includes an additional narrowing of the bandgap due to the presence of the Ge in the base. If it is assumed that the doping-induced bandgap narrowing in SiGe is the same as that in Si, then the activation energy of 44meV obtained for the BJT can be subtracted from 161meV to give an activation energy of 117meV due to the presence of the germanium. This can be compared with a theoretical valence band offset of 117meV and bandgap narrowing of 139meV for 16% Ge

Figure 4 Temperature dependence of the collector current for a Si BJT and a $\text{Si}/\text{Si}_{0.84}\text{Ge}_{0.16}$ HBT

[5]. In a device in which the base is much more heavily doped than the emitter, the conduction band discontinuity protrudes above the conduction band in the base. In this case, the collector current is determined by the valence band offset, rather than the bandgap narrowing. This is the case in our HBT device, where the base doping of $6 \times 10^{18} \text{cm}^{-3}$ is heavier than that in the emitter of $1 \times 10^{18} \text{cm}^{-3}$. The activation energy in fig.4 should therefore be closer to 117meV than 139meV.

Fig.5 shows the temperature dependence of the intrinsic base sheet resistance for a Si BJT with an ion implanted base. A large increase in base sheet resistance can be seen at low temperatures, which was not observed in the device in fig.3 with the epitaxial base. This indicates that freeze-out is more important in this device as a result of a lower doping concentration in the base. An additional contribution to the freeze-out could also come from the dopant in the tail of the ion implanted base profile. This contribution is not seen in the epitaxial base device because the base profiles much sharper.

Figure 5 Temperature dependence of the intrinsic base sheet resistance for a BJT with an ion implanted base

Figure 6 Temperature dependence of the collector current for a Si bipolar transistor with an ion implanted base

Fig. 6 shows the temperature dependence of the collector current for the Si BJT with an ion implanted base. In this case, the characteristic is not linear, and the activation energy decreases at low temperatures. This result can be explained by tails on the ion implanted doping profile which are not present on the epitaxial profiles. The tails on the base profile increasingly dominate the device behaviour as the temperature decreases, with the result that the activation energy decreases. This conclusion is supported by the results of device simulations.

4. References

- [1] C.D.Thurmond; Jnl Electrochem. Soc. vol 122, p1133 (1975)
- [2] N.D.Arora, J.R.Hauser, D.J.Roulston; IEEE Trans. Electron Devices, ED-29, p292 (1982)
- [3] D.B.M.Klaassen, J.W.Slotboom, H.C.De Graaff; Solid State Electronics, vol 35, p125 (1992)
- [4] S.E.Swirhun, Y.H.Kwark, R.M.Swanson; IEDM Technical Digest, p24 (1986)
- [5] R.People; Phys. Rev. B, vol 32, p1405 (1985)