

The Double-Bandgap-Narrowing Transistor

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Abstract

A new type of bipolar transistor is presented featuring a base which is heavily p- and n-type doped at the same time. Two impurity bands will form and cause their own bandgap-narrowing. The two values will add up and lead to a total bandgap reduction of up to 200meV in the base if doping levels around $1E20$ are assumed. This compares to a SiGe HBT with 15% germanium however without the problems of strain relaxation, epitaxy, outdiffusion etc.

A first experimental device of the double bandgap narrowing transistor has been grown by MBE. Measurements on fabricated devices however do not show the expected value of bandgap narrowing in the base. Probable reasons are discussed.

1. Introduction

It started as a student's mistake when running a device simulation software: He had accidentally introduced p- and n-doping at the same time into the base of an SiGe HBT and got unexplainably large gains. It turned out that the software had simply added the apparent bandgap narrowing (ABGN) values from its parameter list. When reconsidering a practical device however it was quickly realised that a transistor similar to a SiGe HBT should be possible without any germanium. Using doping levels in the range of $5E19$ to $2E20$ which is common for HBTs one should expect twice the ABGN-values [1] of 80 - 100meV from both p and n-dopings, i.e. up to 200meV bandgap reduction in the base. For comparison a SiGe HBT would need about 15% germanium for the same performance. In the following an npn double bandgap narrowing transistor (DBGNT) will be considered which has a net excess p-doping in the base.

A more detailed look into theory reveals that the bandgap narrowing (BGN) calculated from the impurity bands is even higher (150meV for $1E20$) [2]. In practice however the ABGN value has to be used due to the Fermi-Dirac-correction [2]. In the case of the DBGNT this applies only to the valence band whereas at the conduction band the full BGN value instead of the

ABGN has to be used. This is because the performance of a bipolar transistor is determined by minority carrier transport across the base. The electron quasi fermi level does not enter deeply into the conduction band as the Kirk effect keeps the minority carrier concentration below $1E18$.

Let us consider a practical device with $N_a=1E20$ and $N_d=5E19$. This leads to p-ABGN = 92meV and n-BGN = 120 meV giving a total ABGN of 212meV. In the next sections we describe fabrication and measurements of a similar device.

2. Experiment

A DBGNT layer structure was grown by MBE on a 4 inch n+ substrate. Collector and emitter were 100nm thick, doped $1E17$ and $1E18$, respectively. At the surface there was a 25nm n+ emitter contact layer. The base was 25 nm thick and simultaneously doped with $1.1E20$ boron and $5E19$ antimony as can be seen in the SIMS profile in Fig.1. The boron tail into the collector

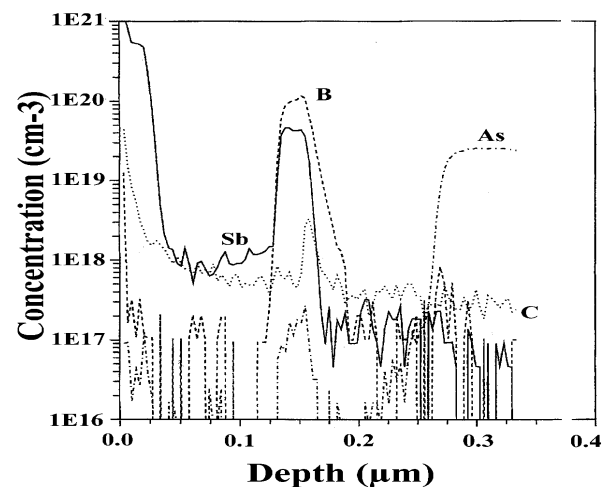


Fig.1: SIMS profile of the experimental DBGNT

is probably a SIMS artefact as both dopant sources were switched on at the same time during growth and there were no high temperature anneals afterwards that could have caused a diffusion. The steep leading edge is another proof for the lack of diffusion.

Devices were fabricated using a double-mesa technology similar to the one used for SiGe HBTs /3/. Access to the base is achieved by a wet chemical KOH etch which stops on the p+ layer. The selectivity however is not as high as in the case of a SiGe layer. Differently sized devices from $2\text{-}20 \times 10^{-5}\text{cm}^2$ were bonded into ceramic chip packages and hermetically sealed with silicone plastic. The Gummel plots (Fig. 2) of the devices showed a maximum current gain of 2 and had ideal collector currents down to 10pA.

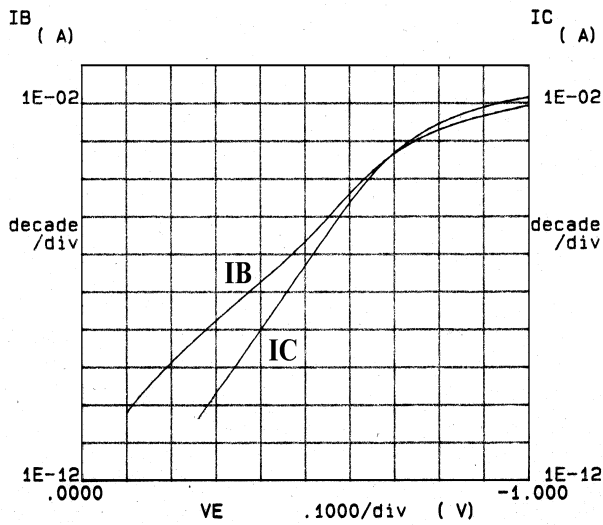


Fig.2: Gummel plot of a DBGNT ($A=2 \times 10^4 \mu\text{m}^2$)

For an evaluation of the base bandgap the temperature dependence of the collector saturation current J_s has to be determined. In the expression for J_s

$$J_s = q \mu_n V_T G_B^{-1} n_i^2 \exp(\text{ABGN}/kT)$$

the $\exp(\text{ABGN}/kT)$ term can be determined independently of the unknown values minority mobility μ_n and base Gummel number G_B^{-1} if J_s is measured at two different temperatures. This was done by immersing the samples in a temperature bath which was controlled with an accuracy of 0.01°C by a high precision calibrated thermometer. Gummel plots of the devices were recorded at 25°C and 90°C with an HP 4145B parameter analyser. Note that a temperature measurement error of only 1°C would change the calculated base bandgap error by 22meV! The V_{be} value is very sensitive too, an error of 1mV corresponds to a 5meV shift. As the resolution of the parameter analyser is only 1mV, the exact V_{be} value was measured separately with a digital voltmeter.

J_s was determined by extrapolating the $J_c(V_{be})$ curve in the Gummel plot. However the collector ideality factor is not exactly one due to the V_{be} -dependent depletion of the neutral base /4,5/, especially in the case of low base dopings in the $1\text{E}18$ range. Typical values of $n=1.002$ to 1.010 will cause extrapolation errors. This can be avoided if the extrapolation is always done at the same V_{be} value.

Several slightly different formulas for n_i^2 can be found in the literature however the ABGN values of reference /1/ are only correct when the equation

$$n_i^2 = 9.62 \times 10^{32} T^3 \exp(1.206\text{eV}/kT)$$

is used. The temperature dependence of μ_n has been assumed to be T^{-1} as confirmed both by experiment and theory /6,7/.

To be sure that the obtained ABGN values are correctly measured several bipolar junction transistors (BJT) were added as control samples and their bandgap narrowing values were determined and compared with literature values. The BJTs had different base dopings from $3\text{E}18$ to $1\text{E}20$. Fig. 3 shows the SIMS of a BJT with $2\text{E}19$ base doping.

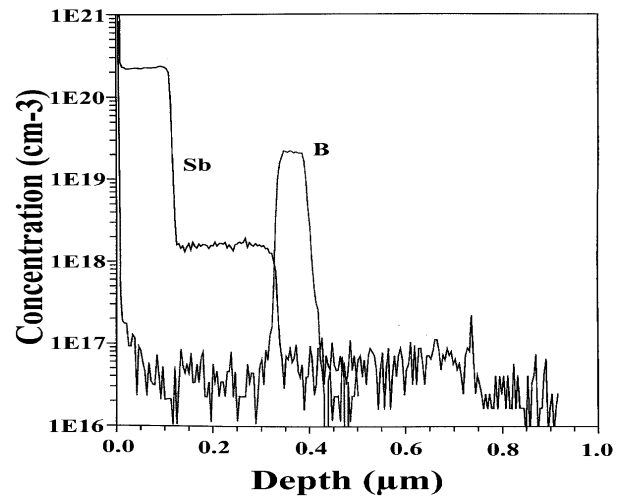


Fig.3: SIMS profile of a control BJT with $2\text{E}19$ base doping

3. Results and Discussion

Fig. 4 shows the measured ABGN values of all devices as a function of the base doping. The DBGNT has been placed at $7\text{E}19$ as this is its net base doping calculated from the SIMS integral values of $2.88\text{E}14$ for B and $1.11\text{E}14$ for Sb. The dashed line is the universal ABGN curve from reference /1/. All BJT samples lie within 10meV on the expected curve.

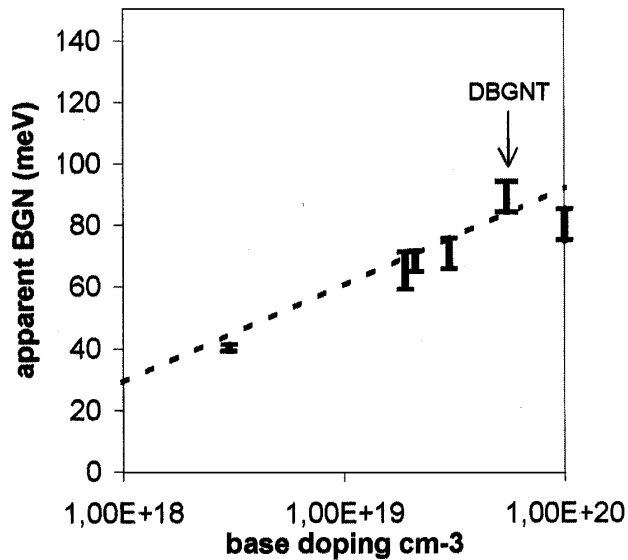


Fig.4: Measured apparent BGN values of the DBGNT and several control BJTs

The DBGNT however does not show the expected bandgap narrowing close to 200meV. Instead it can be found on the Klaassen-curve as if it had only the net $7E19$ p-doping in the base. Possible explanations could be:

- 1) The electrically active doping concentrations are much lower than the SIMS values from Fig.1. There is little evidence for this assumption because the measured base sheet resistance of $1.0k\Omega/\text{square}$ indicates a high degree of activation. The theoretical resistance of a 25nm thick $7E19$ B-doped layer is $600 \Omega/\text{sq}$, i.e. at least 60% of the acceptors are activated. Taking into account a reduced mobility due to the Sb impurities the percentage is even higher.

- 2) Boron and antimony atoms form neutral cluster pairs and become inactive as dopant sources. Only the net surplus boron atoms remain as active impurities. The formation of such pairs could be favoured in the MBE as there is almost a monolayer Sb present on the surface during growth.

- 3) The formation of two impurity bands is not supported by the bandgap narrowing theory. The task remains to theoretically prove this.

4. References

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