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Low Temperature Operation of a Si HBT

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Low-temperature operation of Si heterojunction bipolar transistors (HBTs) with hydrogenated microcrystalline Si (μc-Si:H) emitters is reported. Unlike homojunction transistors, the μc-Si:H HBT can be operated normally even at liquid nitrogen temperature. An ECL ring oscillator with μc-Si:H HBTs has been fabricated for the first time to our knowledge. A propagation delay of 370 ps at 4.2 mW power dissipation is obtained at 83 K.

1. Introduction

Low-temperature operation of Si bipolar devices has many advantages such as improved transconductance and reduced interconnection delay. The recent revolution in superconductive materials now makes superconductive interconnects between cooled bipolar devices possible. However, most Si homojunction bipolar devices designed for room-temperature operation suffer serious degradation in current gain at liquid nitrogen temperature (LNT). The main reason for current gain drop-off in Si homojunction bipolar devices is currently understood to be the excess band gap shrinkage in heavily doped emitters [1]. Even if the degradation in current gain could be avoided, carrier freezeout would degrade the speed performance.

An AlGaAs/GaAs HBT is reported to be promising for low-temperature operation because it has a wide gap emitter and a heavily doped base [2) 3)]. A Si HBT using n-type μc-Si:H as a wide-gap emitter has recently attracted considerable attention because it has a higher current gain than a conventional homojunction transistor and a low emitter resistance [4)].

This paper describes the LNT operation of a Si HBT with a μc-Si:H emitter.

2. Characteristics of μc-Si:H at LNT

All devices were tested using a wafer cryo prover varying temperatures between 77 K and 300 K. Before transistor characteristics were measured, the increase in the emitter resistance at low temperatures was estimated. Figure 1 shows

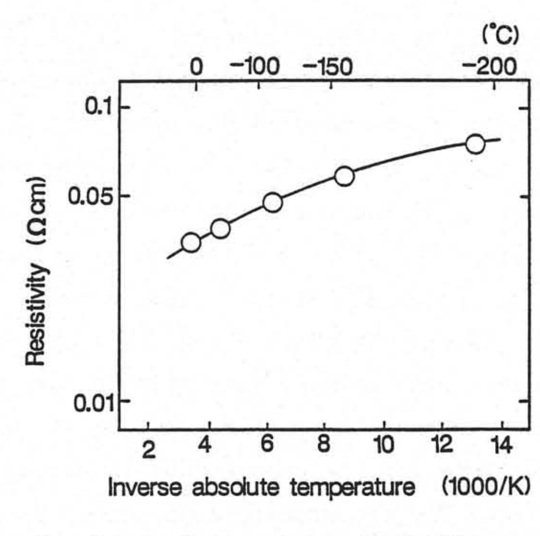

Fig. 1 Resistivity of μc-Si:H film versus inverse temperature.

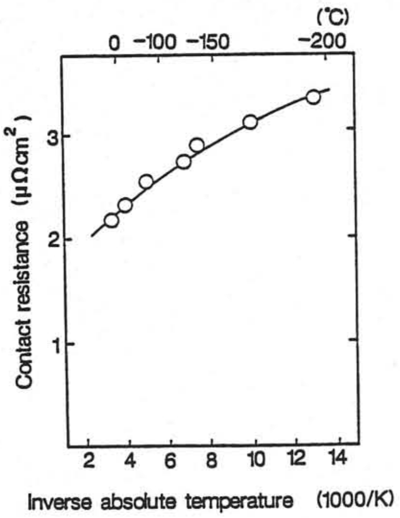

Fig. 2 Contact resistance of μc-Si:H with Al-Si versus inverse temperature.

the temperature dependence of the resistivity of the μc-Si:H film. The resistivity of the μc-Si:H film at LNT is increased only by a factor of two. Hall measurements show this increase in resistivity is due to a degradation in electron mobility. Figure 2 shows the temperature dependence of the contact resistance of the μc-Si:H with Al-Si. The contact resistance is increased by less than a factor of two. These results indicate that the increase in the emitter resistance of the present HBT is expected to be small.

3. Transistor characteristics at LNT

The device structure and fabrication processes of the μc-Si:H HBT were similar to those described earlier [4]. The base sheet resistance of the sample is about 5.0 kΩ/□ .

Figure 3 shows Ic-Vce characteristics of the μc-Si HBT at room temperature and LNT. Note that the μc-Si:H HBT operates normally even at LNT. The variation of the maximum common emitter current gain with temperature for the present HBT is shown in Figure 4. The temperature dependence of the maximum current gain for the present HBT is

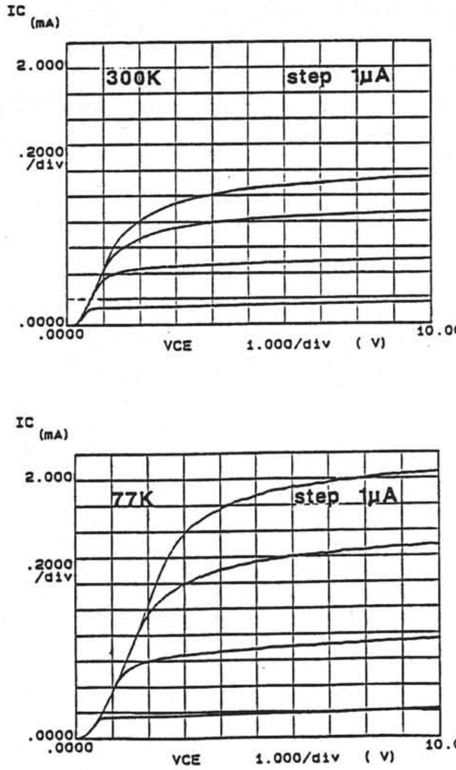

Fig. 3 Common emitter Ic-Vce characteristics of μc-Si:H HBT at room temperature and LNT.

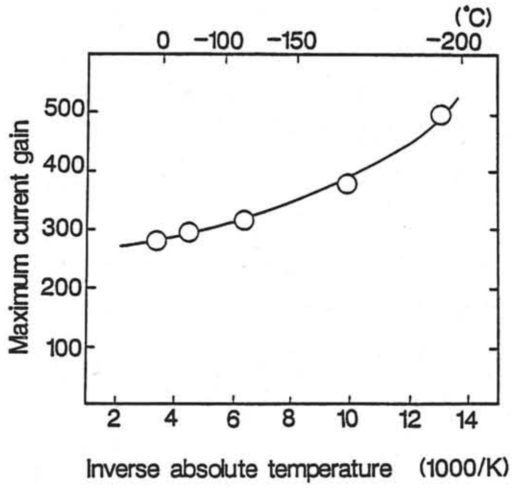

Fig. 4 Maximum current gain of μc-Si:H HBT versus inverse temperature.

much smaller than what is normally observed in homojunction transistors in which the gain decreases exponentially with decreasing temperature. This result indicates that the hole injection from the base into the emitter is suppressed by the effect of the wide gap emitter. At low temperatures, however, the current dependence of the current gain due to carrier recombination becomes larger. These recombination centers must be avoided for practical use.

4. ECL ring oscillator

To investigate the speed performance of the μc-Si:H HBT at LNT, an ECL ring oscillator with μc-Si:H HBTs was fabricated. This is the first IC made with Si HBTs to our knowledge.

The schematic cross section of the HBT is shown in Figure 5. Only conventional bipolar IC processes were used, except for the emitter formation steps. A heavily doped base was used to avoid the carrier freezeout. The base regions were formed by implanting boron ions with doping densities of 5×10^{13} cm^{-2}. This was followed by 900°C annealing for 30 min to activate the implanted species. The peak base doping concentration was estimated to be 7×10^{18} cm^{-3} using a process simulator, and the base sheet resistance is 1.9 kΩ/□ . The minimum emitter size of the HBT is 1.6×6 μm^2. Two-layer metalization processes including a barrier metal were used to get the interconnection. The highest process temperature after μc-Si:H deposition was set at 450°C.

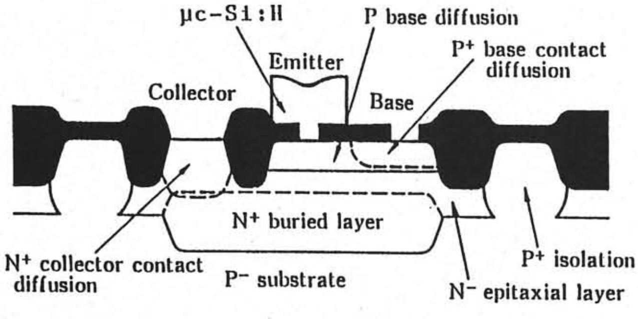

Fig. 5 Schematic cross section of μc-Si:H HBT.

The common emitter current gain of this sample at room temperature is somewhat smaller than that previously reported [4]. This smaller current gain may be due to the detachment of hydrogen during the multimetalization processes. The thermal stability of hydrogen incorporated in the μc-Si:H film must be improved. The emitter resistance at room temperature measured by the collector open method is 30 Ω . This value is almost the same as that of a conventional poly Si emitter transistor.

The supplied voltage V_{EE} of the present ring oscillator was set at -5.2 V. Figure 6 shows output waveform of the 7-stage ring oscillator at 83 K. From this figure, one can see that this ring-oscillator can be operated normally even at low temperatures. The propagation delay time at a power dissipation of 4.2 mW/gate was estimated to be 370 ps. The use of a μc-Si:H emitter allows bipolar circuit operation even at low temperatures. The combination of a μc-Si:H emitter and advanced self-aligned technology, like ESPER (Emitter-base Self-aligned structure with Polysilicon Electrodes and Resistors), is expected to result in higher speed operation even at low temperatures [5].

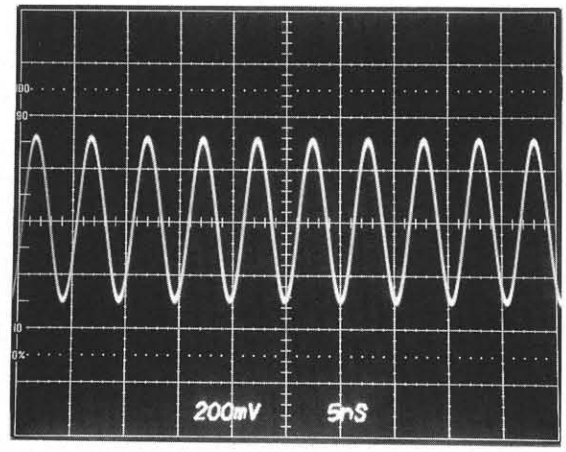

Fig. 6 Output wave form of 7 stage ring oscillator with μc-Si:H HBTs.

5. Conclusions

A Si HBT with a μc-Si:H emitter can be operated normally even at LNT. The temperature dependence of the common emitter current gain is much smaller than what is normally observed in homo-junction transistors. An ECL ring oscillator with a propagation delay of 370 ps at a power dissipation of 4.2 mW at 83 K was demonstrated. There still remains the problem of thermal stability of μc-Si:H film.

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