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Multi-step Bidirectional NDR Characteristics in $Si/Si_{1-x}Ge_x/Si$ Double Hetero-Structures

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This paper reports novel negative differential resistance (NDR) phenomena observed at room temperature in strained base $n\text{-}Si/p\text{-}Si_{1-x}Ge_x/n\text{-}Si$ double heterojunction bipolar transistors (DHBTs): a strong and symmetric bidirectional NDR modulated by base bias, together with a multi-step characteristic in collector current I_C vs emitter-collector bias voltage V_{CE} in the devices with very thin base. Their temperature dependence has been measured to identify the possible transport mechanism. The physical origins of these phenomena are analyzed.

I. Introduction

$Si_{1-x}Ge_x/Si$ heterostructure system has drawn great interest recently. The development of molecular beam epitaxy (MBE) made it possible to grow thin layers of dislocation free strained $Si_{1-x}Ge_x$ alloys on a Si substrate,[1),2)] and $Si/Si_{1-x}Ge_x/Si$ bipolar transistors have been successfully fabricated in several laboratories using different configuations,[3),4),5)] extending the bandgap engineering into Si technology.

In our DHBT structures with a base thickness ~ 4000 Å, a normal transistor action with typical common emitter current gain β ~ 15 was demonstrated.[4)] As the base thickness is considerably deduced, a novel transport phenomenon was observed: the I_C - V_{CE} curve of the very thin base structure near breakdown is modified into a multi-step fashion, showing bidirectional NDR simutaneously. The results from the later structure will be analyzed in the following.

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II. Device Structure and Fabrication

A layer structure of the MBE grown $Si/Si_{1-x}Ge_x/Si$ DHBT devices with inverted emitter/collector configuration and its band diagram at equilibrium are given in Fig. 1. An n^+-Si emitter layer was first grown on the substrates at 770°C, followed by a strained thin $p\text{-}Si_{0.9}Ge_{0.1}$ layer grown at 650°C. The top two layers are the collector and contact respectively, grown at 700°C.

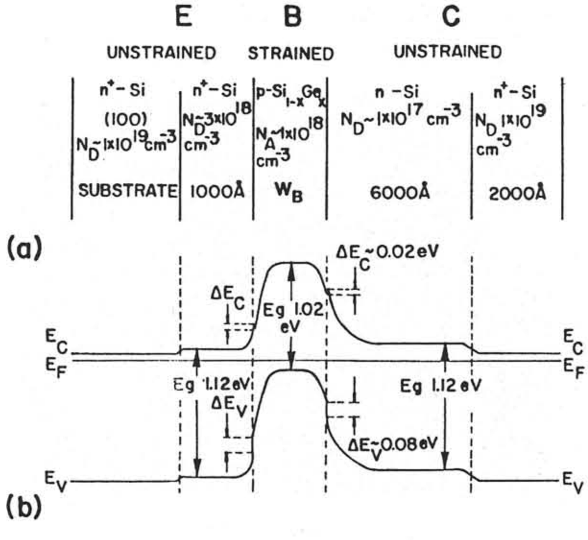

Fig. 1: (a) Device layer structure;
(b) Band diagram at equilibrium.

The mesa configuration devices were made by wet etching technique and the etching depth was monitored by hot probe measurements. The active areas of the n-p-n device structures are ~20×30 μm^2. The passivation film is SiO_2 made by low-temperature plasma-enhanced CVD, followed by an annealing at ~ 500°C for one hour. Aluminum was used for metallization.

It is found experimentally that the effective base thickness W_b is not uniform on our wafers. From the thickest side, W_b^{max} ~ 1600 Å, it gradually decreases below the detection limit on the other side.

III. Measurement Results and Discussions

The measurements were carried out in the dark with a load resistance R_L, using a curve tracer and a Semiconductor Parameter Analyzer HP-4145B. Some typical results are described as follows:

(1). For the devices with intermediate W_b, when V_{CE} increases, the device can be switched from an "off" state to an "on" state in both bias directions, showing a strong and quite symmetric bidirectional bistability characterized by a large NDR region (Fig. 2). The turn-on voltage V_{CE}^T is usually 5-10 V for a floating base configuration.

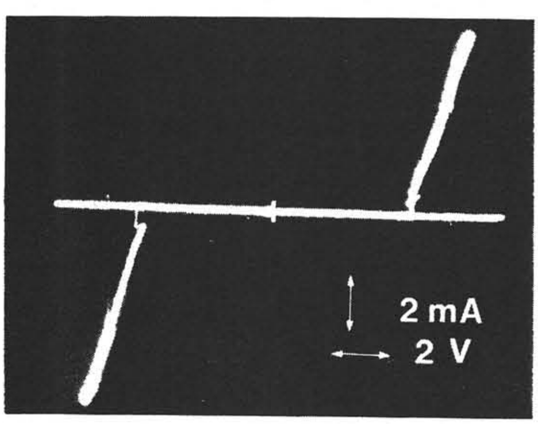

Fig. 2: Bidirectional bistability I_C-V_{CE} curve for floating base.

It is known that I_C of a bipolar transistor in common emitter configuration, incorporating the ionization, is [6)]

$$I_C = \frac{(\beta+1)M}{1-\beta(M-1)} I_{CO} \qquad (1)$$

I_{CO} is the collector reverse saturation current, M is the avalanche multiplication factor. When V_{CE} is increased, M becomes greater. The holes created in the BC depletion region by ionization are swept into the base, accumulate there representing an effective increase in base current, $(M-1)I_C$. In a $Si/Si_{1-x}Ge_x/Si$ DHBT these holes are trapped in the base region more strongly due to the existence of ΔE_V at the $Si/Si_{1-x}Ge_x$ heterojunctions. Consequently, these holes modulate the bias across the EB junction and cause an electron current, $\beta(M-1)I_C$, to be injected from the emitter. Because there is a band discontinuity ΔE_g at the EB heterojunction, the injection efficiency is higher than in a homojunction. As the injected electrons pass through the BC depletion region, secondary electron-hole pairs are created by ionization, forming a positive feedback loop. When V_{CE} is large enough, $\beta(M-1)$ might be larger than unity and I_C would grow infinitely. This does not happen. Instead the device modulates itself by decreasing M, keeping $\beta(M-1)=1$ to achieve a stability and the device jumps from the "off" state in its "on" state. When EC is reverse biased, the device still has strong current amplifying function and in turn shows large NDR. The existence of ΔE_V at the $Si_{1-x}Ge_x/Si$ BC heterojunction can still trap holes in the base region efficiently and keep a high injection efficiency even when the base doping is larger than the collector doping (i.e, when the collector acts as an emitter), keeping $\beta(M-1)=1$. This seems to be an important reason why a symmetric and strong bidirectional bistability is obtained in these DHBTs, in spite of their unsymmetric dopings.

(2). For the devices with small W_b, the I_C-V_{CE} curve shows clear multi-step NDR characteristics in both "off" and "on" states as shown in Fig. 3.

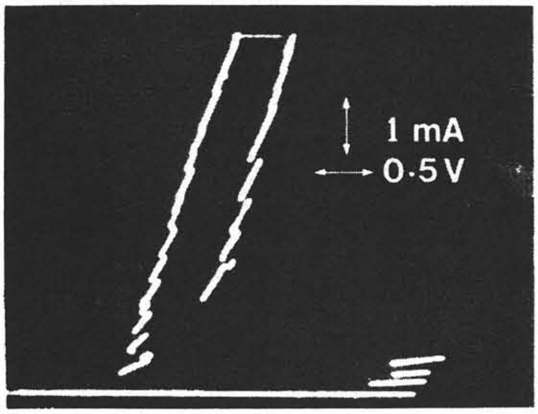

Fig. 3: Multi-step characteristic curve of very thin base structures for floating base. The multi-step starting voltage V^0_{CE}~6V. Part of the I-V curve, corresponding to decreasing the voltage, has been shifted to the left to separate it from the overlapping part for increasing voltage.

Here we suggest a possible explaination. When V_{CE} is increased, the BC depletion region width increases, and the neutral base width is reduced, producing a narrow hole potential well in the DHBT's thin base. The existence of ΔE_V makes the well deeper. The valence bands of the thin base can be quantized into many sub-bands in the potential well at high V_{CE}. The electrons from each of these sub-bands tunnel sequentially through the reverse biased BC junction and produce the steps in the I_C-V_{CE} NDR curve shown in Fig. 3. At the same time, the holes, generated in the sub-bands by the electron tunneling, move towards the EB junction. To keep the current continuity, electrons in the emitter conduction band are injected into the base valence band via defect assisted recombination-tunneling and other recombination processes at the EB junction and base, and depopulate the sub-bands. We have calculated these sub-band energies, and estimated the energy seperation ΔE_n of sub-bands giving tunneling to be around 20 ~ 50 meV. The detailed calculation will be presented elsewhere.[7)] From that, we can calculate the turn-on voltage V^T_{CE} ~ 10 V and step length ΔV^n_{CE} ~ a few hundreds of millivolts. These estimates are in agreement with the experimental values shown in Fig.3. The NDR between the steps is thought to be caused by a similar mechanism mentioned above.

(3). The temperature dependence of I_C-V_{CE} curves were examined to study the possible mechanisms of breakdown and steps. As shown in Fig. 4, at low temperature the feature of

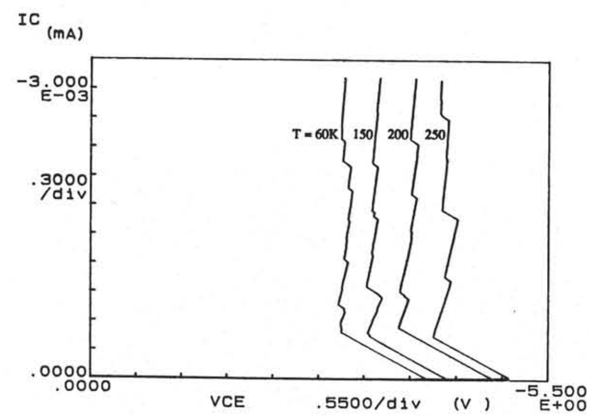

Fig. 4: I_C-V_{CE} curves (for increasing voltage) at different temperatures.

the multi-steps become slightly weaker and some new small steps appear visible. These results can be considered as a support to the explaination that the steps origin from tunneling. As we know, interband tunneling probability possesses a positive temperature coefficient and avalanche multiplication facotr M has a negative temperature coefficient. When the temperature is reduced, the propotion of tunneling current in total collector current I_C decreases. At low temperature, I_C is the superposition of a small steped tunneling current on top of a large avalanche current, so I_C-V_{CE} curve shows weaker steps.

(4). When a base bias V_B is applied, the V_{CE}^T decreases in both directions with V_B and the whole I_C-V_{CE} curve is moved towards Y axis as shown in Fig. 5.

If a V_B is applied on the device, the potential barrier at the EB junction is lowered, the emitter electron injection and then I_C are increased. The requirement $\beta(M-1) = 1$ can be satisfied at a lower voltage V_{CE}^T, and the device can be switched from the "off" state to its "on" state earlier. It is also easier to keep the "on" state at lower V_{CE} for the same reason. This means the I_C-V_{CE} curve is moved towards the Y axis. With V_B increasing, the I_C-V_{CE} curves are moved closer and closer to the Y axis, resulting in the clear group of bidirectional bistability curves in Fig. 5.

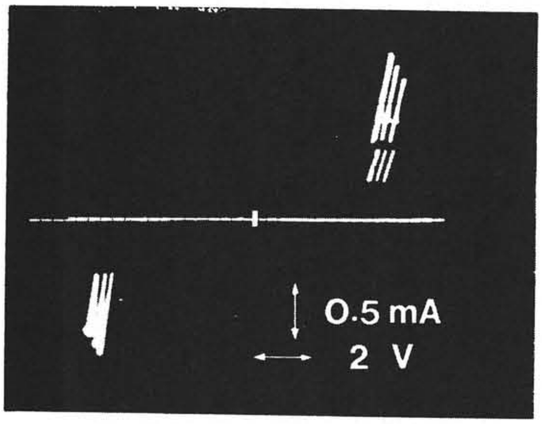

Fig. 5: Base bias modulation effect, which is shown by a set of I_C-V_{CE} curves for different V_B. The step curves closest to the center correspond to the highest V_B.

V. Conclusion

A strong and symmetric bidirectional NDR modified into a multi-step fashion has been demonstrated in $Si/Si_{1-x}Ge_x/Si$ DHBTs. They can be modulated by base bias. The NDR phenomenon is the joint effects of avalanche multiplication and transistor gain, and also related with the heterojunction band off-sets of these DHBTs. The steps are proposed to be caused by electrons tunneling sequentially from the sub-bands of the quantized base valence bands, through the reverse biased BC junction to the collector. The temperature dependence of the I_C - V_{CE} curve appears to support the proposed explaination.

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