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Atomic Layer Epitaxy Grown Heterojunction Bipolar Transistor Having a Carbon Doped Base

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Atomic Layer Epitaxy is a relatively new growth technique that allows one to obtain monolayer control of epitaxial films thicknesses by growing from a self limiting process. In addition to accurate thickness control, if a trimethylgallium source is used as the adduct source for the growth of GaAs, carbon can be incorporated into the epitaxial layer as an acceptor. Using this technique we have been able to realize heterojunction bipolar transistor with carbon doped bases. The low diffusivitivy of carbon with respect other known p-type dopant makes this an attractive technology for high performance heterojunction bipolar transistor applications.

Enhanced performance can be obtained from many of todays electronic and optoelectronic devices by precisely controlling the doping and alloy composition profile. This control is particularly critical for heterojunction bipolar transistor where a wide band gap emitter is used to enhance the emitter injection efficiency into a narrow band gap base. In a N-p-n transistor the valence band discontinuity at the emitter/base junction enables one to dramatically increase the base doping and hence decrease the base resistance leading to a significant improvement in the high frequency performance of the device. The enhancement of the emitter injection efficiency relies on the superposition of the heterojunction and homojunction. A small displacement of either junction will significantly effect the injection properties of the emitter leading to a dramatic suppression of the gain.

For this reason it is important that the impurity species used to dope the transistor region be immobile. This does not present a problem when n-type dopants such as Si are used, since they are relatively immobile. However, most of the conventional p-type dopants have high diffusion coefficients the least mobile is Be with a diffusion coefficient of $1x10^{-15}$ at $800^{o}C$[1]. At the high doping concentrations required for the base of a high performance N-p-n transistor the out diffusion of this dopant into the emitter displaces the p-n junction from its desired position decreasing the emitter injection efficiency and dramatically lowering the current gain. As an alternative to the conventional base dopants we have chosen to consider carbon since it has a much lower diffusion coefficient. It has recently been reported that the diffusion coefficient of carbon in GaAs is about $2x10^{-16}cm^2s^{-1}$ at $800^{o}C$[2] which is five times smaller than the diffusion coefficient of Be. The Carbon was incorporated into the GaAs base of a GaAs/AlGaAs transistor using Atomic Layer Epitaxy (ALE).

It has recently been reported that the

growth of GaAs from a trimethygallium (TMG) source makes it possible to obtain heavily doped carbon layers with excellent thickness and doping uniformity across a substrate[2-4]. The doping is believed to result from the formation and subsequent incorporation of partially cracked TMG in the form of metal carbide under the specific conditions used for ALE. We have used this property of the growth to form a HBT having an emitter and collector grown by conventional OMCVD and a base grown by ALE. A similar approach has recently been used to grow a GaAs/AlGaAs quantum well laser[5].

The epitaxial layers were grown in a horizontal atmospheric pressure reactor equipped with a fast switching manifold. The epitaxial layers were grown on Semi-insulating GaAs substrates polished 6^{o} off the (100) axis. The reagents used for the growth were TMG, trimethylaluminimum (TMA) and Arsine. The carrier gas was Pd-diffused hydrogen. Diethyltelluride diluted to 50ppm in hydrogen was used as the n-type dopant for both the emitter and collector layers. The sample comprised a 1um n^{+} buffer layer followed by the growth of a 500nm collector doped to $2x10^{17}cm^{-3}$. Both these layers were grown conventionally at $700^{o}C$. The temperature of the substrate was then rapidly cooled to $550^{o}C$ over a period of 120s while maintaining the arsine flow. A base layer approximately 120nm thick was then grown by alternately flowing TMG and AsH_3 for 1sec 200 times. Previously we have found that the two reagents do not mix in the growth phase. Following the growth of the base the substrate temperature was increased to $750^{o}C$ in 75s so that the emitter could be grown conventionally. The Aluminum composition in the emitter at the base edge was increased from 0 to 30% over 30nm in order to enhance the emitter injection efficiency and decrease the built-in potential for electrons[6]. A final thin n^{+} contact layer was grown on the emitter to facilitate ohmic contact formation.

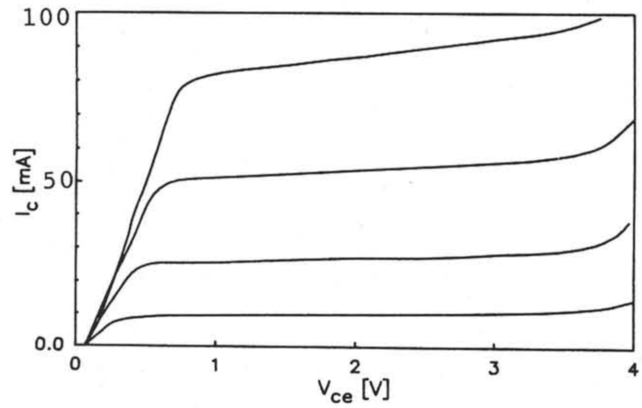

Fig.1 Common-emitter characteristics of the ALE grown GaAs base heterojunction bipolar transistor. The base current was stepped in intervals of 200μA. The emitter junction had a diameter of 100um.

The layer was fabricated into a two level mesa structure using standard chemical etching techniques with the emitter having an area of $7.85x10^{-5}cm^{-2}$. The ohmic contacts were formed by thermally annealing a Au-Sn alloy to the emitter and collector regions and a Au-Be alloy to the base.

The common emitter characteristics of the HBT are show in Fig. 1. As can be seen there is a significant increase in the common emitter current gain with increasing collector current indicating strong recombination. This effect can be highlighted by plotting the gain dependence on collector current. As can be seen there is a strong dependence with the gain increasing from 10 at 200μA to just over 100 at 100mA.

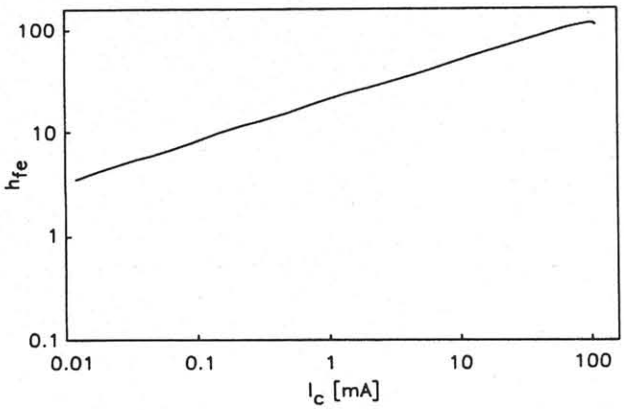

Fig. 2 Small signal gain (h_{fe}) of the ALE grown transistor. The transistor had a common emitter gain of 105 at a collector current of 100mA.

The strong dependence of the current gain is a direct result of the poor interfacial properties of the emitter junction resulting from the exposure of the base/emitter interface whilst the substrate temperature is being ramped up for the conventional growth of the emitter. We have observed similar current/voltage characteristics for conventionally grown junctions with the same hold time. If we assume an emitter injection efficiency of unity, which is a overestimate for this device, we can infer that the diffusion length for minority carriers in the base is at least 1.4μm. Which is typical of conventional grown HBT's indicating that the low growth temperature used for ALE does not degrade the minority carrier transport properties.

We believe the low injection efficiency of the emitter/base junction could be eliminated by using ALE to grow the whole structure. This can be realized by using both TMG and Triethylgallium (TEG) as the gallium source and Triethylaluminum (TEA) as the source of Al. It is known that the incorporation of carbon from TEG and TEA growth sources at growth temperatures of 550°C is minimal[7]. Hence, this source of gallium and aluminum would be used to form the emitter and collector whilst the base would be grown from a TMG source. This growth process would avoid delay when changing from base to emitter deposition.

In conclusion we have fabricated a GaAs/AlGaAs HBT having a carbon doped base. The carbon was incorporated into the base in a novel way using the partially reacted TMG to incorporate metal carbide. Current gains in excess of 100 were obtained at current densities of $1300Acm^{-2}$.

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