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New Technologies of a WSi Base Electrode and a Heavily-Doped Thin Base Layer for High-Performance InGaP/GaAs HBTs

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Two new technologies of a WSi base electrode and a heavily-doped thin base layer for high-performance InGaP/GaAs heterojunction bipolar transistors (HBTs) are demonstrated. The WSi is useful for the fabrication of submicron-wide base contacts. Also, extremely low specific contact resistance under $2 \times 10^{-7}\ \Omega\cdot cm^2$ was attained with hole concentration over $2 \times 10^{20}\ cm^{-3}$. A fabricated HBT with a heavily-doped thin base layer and a gold-based base metal exhibited an f_T of 115 GHz and an f_{max} of 159 GHz, which is the first report of both parameters being over 100 GHz in an InGaP/GaAs HBT. These results indicate that further improvements in high-frequency performance can be achieved by combining these two technologies.

1. Introduction

GaAs-based heterojunction bipolar transistors (HBTs) are much more promising than Si bipolar transistors for high-speed applications because of their superior carrier transport properties[1]. Since scaling down the device size is an indispensable requirement for high-speed and low-power operation, HBTs with an emitter area of less than 1 μm^2 have been fabricated[2,3]. However, their parasitic capacitance is higher than that of double poly Si bipolar transistors due to their larger parasitic region, and this has been a limiting factor in the speed of the smaller devices.

The largest component of the base-collector capacitance frequently originates in the extrinsic base region used to contact the base layer of the transistor. Although the size of the extrinsic base can be reduced by reducing the base contact width, this increases the base contact resistance, which also degrades the high-frequency performance. To reduce the base contact width without increasing the base contact resistance, an extremely high base doping level is required. In addition, a readily processable electrode metal is also required to fabricate base electrodes for narrow contact regions.

In this paper, we describe two new technologies for high-performance InGaP/GaAs HBTs. One is a WSi base electrode and the other is a heavily-doped thin base layer for use in HBTs. While WSi can be used to easily produce base electrodes with submicron-wide base contacts, a heavily-doped thin base layer is also useful to obtain a low contact resistance, a high current gain, a high cut-off frequency, and a high maximum oscillation frequency.

2. Technology of a WSi Base Electrode

In the fabrication of submicron-wide base contacts, WSi is a suitable electrode metal because of its definite advantages over the conventional gold-based electrode metal; i.e., it can be sputtered with good step coverage and selectively patterned using reactive ion etching (RIE). We have fabricated a device structure with a WSi base electrode, and have investigated the contact resistance between WSi and heavily-doped thin p-GaAs layers.

2.1 *Device structure with a WSi base electrode*

Figure 1 shows a cross sectional scanning electron micrograph of the device structure with a WSi base electrode. The emitter mesa was formed by electron cyclotron resonance (ECR) plasma etching using a W emitter electrode as an etching mask. This was followed by the formation of base and collector mesas using ECR plasma. The emitter width is 0.50 μm and the base contact width is 0.35 μm. The outside of the base-collector junction was buried with SiO_2. After a 0.05-μm-thick SiO_2 sidewall was formed to separate the emitter and the base, WSi was deposited by RF sputtering. Finally, the WSi was etched by RIE to form a base electrode. As shown in Fig. 1, WSi covers both the submicron-wide base contact surface and the buried SiO_2 outside of the base-collector junction. This result shows that WSi is useful to fabricate base electrodes for narrow contact regions with buried SiO_2 structures, which can lead to a significant reduction in the base-collector capacitance.

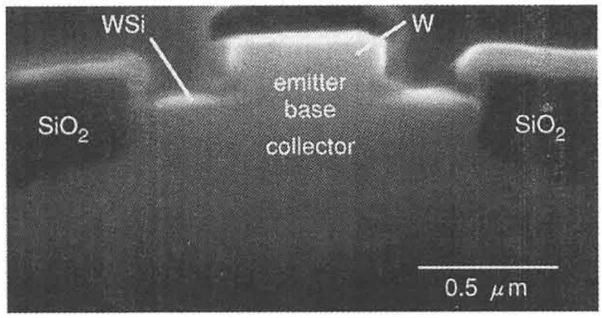

Fig. 1. SEM cross section of a WSi base electrode structure.

2.2 *Contact resistance of WSi*

We investigated the contact resistance between WSi and heavily-doped thin p-GaAs layers by fabricating transmission line model (TLM) devices. p-GaAs layers with 30-nm-thick were grown on semi-insulating (100) GaAs substrates by gas source molecular beam epitaxy (GSMBE). Hole concentrations N_A were 5×10^{19}, 1×10^{20}, 2×10^{20}, and $4 \times 10^{20}\ cm^{-3}$. These layers were covered with n-InGaP so they would have the same structure as an HBT. The WSi thickness was 300 nm. The TLM patterns were isolated by RIE for WSi and wet chemical etching for GaAs and InGaP. The pad width of the TLM patterns was 10 μm, and the spacing between the pads was 2, 4, 8, 16, and 32 μm.

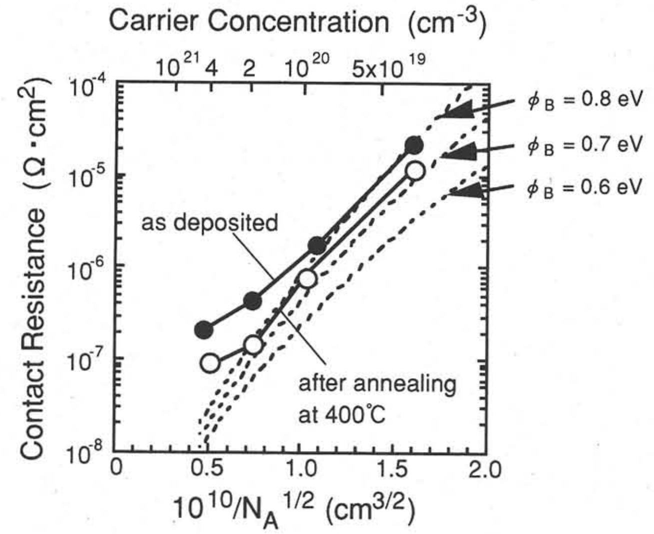

Fig. 2. Contact resistance as a function of carrier concentration N_A in 30-nm-thick GaAs.

We also investigated the effect of annealing for 30 minutes at 400℃ in N_2.

Figure 2 shows the specific contact resistance as a function of carrier concentration. In this figure, theoretical calculations based on a tunneling model[4] are also shown with dashed lines. The calculation was carried out for various potential barrier heights ϕ_B, assuming that the effective tunneling hole mass was 0.1 m, where m is the free electron mass. Although the contact resistance of the as-deposited sample deviated from the theoretical curves, specific contact resistance under $5 \times 10^{-7}\ \Omega \cdot cm^2$ was obtained for $N_A > 2 \times 10^{20}$ cm^{-3}. The contact resistance of the annealed sample, on the contrary, agrees well with the theoretical curve, and extremely low contact resistance under $2 \times 10^{-7}\ \Omega \cdot cm^2$ was attained for $N_A > 2 \times 10^{20}$ cm^{-3}. These results suggest that an ideal WSi/GaAs interface is formed by the annealing. We analyzed the interface by secondary ion mass spectroscopy (SIMS) to clarify this annealing effect. However, no significant difference was observed in the SIMS profiles of samples before and after annealing. We believe the annealing reduced the damage to the GaAs surface that is induced during RF sputtering, and as a result, reduced the contact resistance. More detailed analysis is required to clarify the mechanism of the contact resistance reduction.

3. Technology of a Heavily-Doped Thin Base Layer

A heavily-doped and thin base layer for use in HBTs is indispensable both to reduce extrinsic base regions and to obtain high current gains. When a heavily-doped base layer is used, InGaP/GaAs HBTs are superior to AlGaAs/GaAs HBTs because of the larger valence band discontinuity at the InGaP/GaAs interface, which confines holes in the base more effectively and improves the minority-carrier injcction efficiency. In addition, InGaP/GaAs HBTs are suitable for fabricating small area devices since they show no significant drop in current gain as the device size is scaled down, owing to the smaller surface recombination velocity around the periphery of the emitter-base junction compared to AlGaAs/GaAs HBTs[5]. We have fabricated InGaP/GaAs HBTs with heavily-doped thin base layers, and have investigated their characteristics.

Table I. Layer structures of the fabricated HBT.

Layer	Material	Doping (cm^{-3})	Thickness (nm)
Emitter-cap	n^+InGaAs	4×10^{19}	50
	n^+GaAs	5×10^{18}	50
	n^+InGaP	8×10^{18}	50
Emitter	n^-InGaP	1×10^{18}	50
Base	p^+GaAs	$5 \times 10^{19} \sim 4 \times 10^{20}$	30
Collector	un-GaAs	undoped	200
Sub-collector	n^+GaAs	5×10^{18}	800

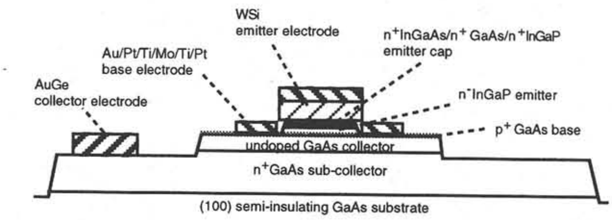

Fig. 3. Schematic cross section of the fabricated HBT.

3.1 *Device structure and fabrication*

The epitaxial layer structure is shown in Table I. The layers were grown by GSMBE. We prepared four types of HBT epilayers with the base concentrations of 5×10^{19}, 1×10^{20}, 2×10^{20}, and 4×10^{20} cm^{-3}. The base thickness was 30 nm. For the p-type dopant, carbon was utilized because of its low diffusion coefficient compared to other p-type dopants[6], which makes carbon suitable for fabricating heavily-doped thin layers. The triple emitter cap layers were used to reduce the emitter resistance. The collector layer was 200-nm-thick undoped GaAs. A thick GaAs sub-collector was used to reduce the collector resistance. Mesa structure devices were fabricated by wet chemical etching and the liftoff process. Figure 3 is a schematic cross section of the fabricated HBT. A self-aligned process, utilizing the side etching of the emitter, was used to form the spacing between the emitter and base metal. In these HBTs, Au/Pt/Ti/Mo/Ti/Pt metal structures were used for base electrodes as in a conventional process.

3.2 *Device performance*

Figure 4 shows a typical Gummel plot of a fabricated HBT with a base doping concentration of 1×10^{20} cm^{-3}. The emitter-base junction area was 1.2×3.4 μm. The collector current exhibits ideal exponential behavior from 10^{-10} to 10^{-3} A, with an ideality factor of 1.0. On the other hand, the ideality factor of the base current is larger than 1.0 because of the surface recombination current in the extrinsic base region. Figure 5 shows the dependence of the current gain on the base doping concentration at a collector current

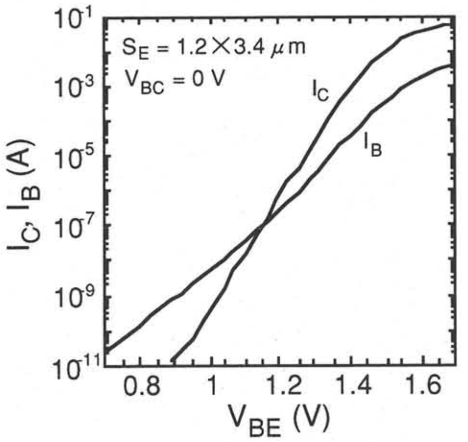

Fig. 4. Gummel plot of the fabricated HBT with a base doping level of 1×10^{20} cm^{-3}.

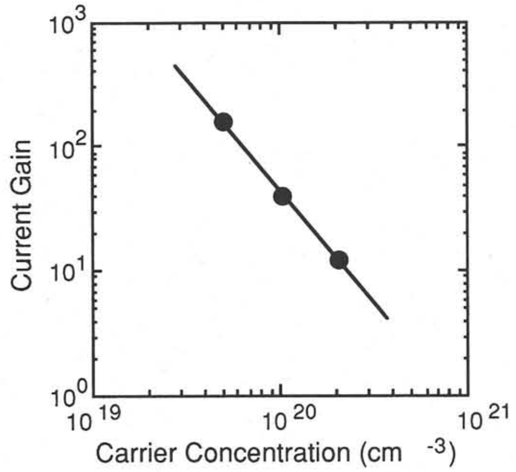

Fig. 5. Current gain as a function of carrier concentration at a collector current of 10 mA.

of 10 mA. Relatively high current gains were obtained by using an InGaP emitter and a thin base layer in spite of very high base doping concentrations. As shown in Fig. 5, the current gain is inversely proportional to the square of the base doping concentration. This indicates that an Auger recombination process dominates in a base layer with a high base doping level. Therefore, for circuit applications, the base concentration should be less than 2×10^{20} cm^{-3} for a 30-nm-thick base layer.

High-frequency characteristics of HBTs with a base doping level of 1×10^{20} cm^{-3} were measured in the frequency range from 100 MHz to 40 GHz. The measurements were carried out at a collector-emitter voltage of 1.6 V. Figure 6 shows the collector current dependence of f_T and f_{max} with an emitter-base junction area of 1.2×3.4 μm. A peak f_T was 115 GHz and a peak f_{max} was 159 GHz. As far as we know, this is the first report of f_T and f_{max} both being over 100 GHz for an InGaP/GaAs HBT. These high-frequency characteristics were achieved by using a heavily-doped thin base layer because it can reduce the base

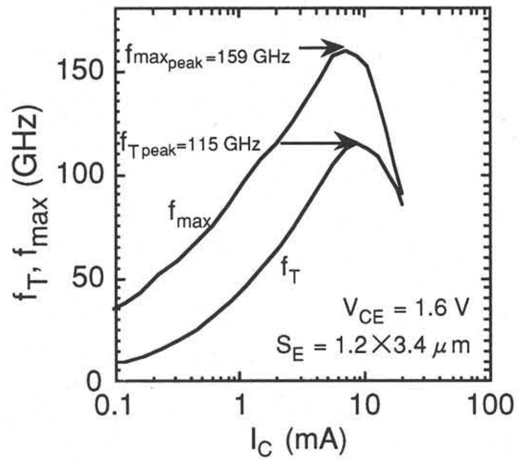

Fig. 6. Dependence of f_T and f_{max} on the collector current of a fabricated HBT with a base doping level of 1×10^{20} cm^{-3}.

transit time and the base resistance, which improves f_T and f_{max}, respectively. As shown in Fig. 3, the fabricated HBT had a relatively large base-collector junction area, which leads to high capacitance. Therefore, we believe that even higher frequency performance can be attained by applying the WSi base electrode technology explained above to reduce the base-collector capacitance.

4. Conclusions

We have demonstrated two new technologies of a WSi base electrode and a heavily-doped thin base layer for high-performance InGaP/GaAs HBTs. We found that WSi is useful for fabricating submicron-wide base contacts and thin p-type GaAs ohmic contacts. Extremely low contact resistance under 2×10^{-7} Ω·cm^2 was achieved with hole concentration over 2×10^{20} cm^{-3} by 30-minute annealing at 400℃. A fabricated HBT exhibited an f_T of 115 GHz and an f_{max} of 159 GHz by using a 30-nm-thick base layer with a doping level of 1×10^{20} cm^{-3}. These characteristics make InGaP/GaAs HBTs a promising candidate for high-speed circuit applications.

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