their high-current drivability. However, their structure is so complicated that it is difficult to fabricate fine devices and high-density IC's. This paper reports a new high-speed device utilizing a 2DEG heterostrucure, which has high-current drivability as well as a simple device structure.

The new device has an n-AlGaAs/GaAs selectively doped heterostructure with a p^+ GaAs ($N_A = 3 \times 10^{19}$ cm^{-3}) hole injection electrode between a couple of Ni/Au-Ge ohmic contacts to the heterostructure. This structure is fully planar and similar to that of a p^+ gate selectively doped structure FET [1]. However, the n-AlGaAs layer is so thin (300 Å, $N_D = 2 \times 10^{18}$ cm^{-3}) that there are scarcely any electrons in the entire region of the heterostructure in thermal equilibrium. When a lot of holes were injected to this heterostructure, a high-current mode operation was achieved. A device with a 0.5 μm × 100 μm p^+ hole injection electrode exhibited extremely high transconductance of 3000 mS/mm for FET mode operation at 300 K. Current gains for bipolar transistor mode operation (β) were 25 in the low-current level and $6 \sim 8$ in the high-current level. The maximum current exceeded 1 A/mm, which is about two times larger than that for GaAs MESFET's and 4 times larger than that for selectively doped structure FET's.

This operation mode is considered as follows. Injected holes will induce the same amount of electrons in the heterostructure, especially in GaAs side due to the conduction band discontinuity. These electrons flow along the herterointerface, like 2DEG between a couple of ohmic contacts. The current gain is possibly proportional to the ratio of a high saturation velocity of electrons to a low drift velocity of holes. Therefore, the AlGaAs/GaAs heterostrucure is advantageous in regard to current gain over a lateral GaAs transistor reported recently, which is also operated by hole injection [2]. The new device has further advantages of simpler device structure, simpler fabrication process, and possibly lower parastic capacitance due to the depleted n-AlGaAs layer. High-frequency and high-speed performances will be presented.

[1] K. Ohata *et al.*, in *Microwave Symp. Dig.*, p. 434, 1984.
[2] K. Taira *et al.*, in *IEDM Tech. Dig.*, p. 201, 1984.

VA-5 Pseudomorphic GaInAs/GaAs Single Quantum Well High Electron Mobility Transistor—J. J. Rosenberg and M. Benlamri, Department of Engineering, Brown University, and P. D. Kirchner, J. M. Woodall, and G. D. Pettit, IBM Thomas J. Watson Research Center.

Modulation-doped semiconductor heterojunctions have led to a variety of high-mobility two-dimensional electron gas transistors with improved performance over conventional MOSFET's and MESFET's. To date, the best material and device results come from heterojunctions between n-doped GaAlAs and undoped GaAs. However, these structures exhibit undesirable persistent photoconductivity attributed to deep levels that unavoidably result when GaAlAs is doped n-type. This problem is overcome only by using undoped GaAlAs layer(s). Additional difficulties include maintaining heterointerface abruptness while growing high-quality GaAlAs, making "inverted" GaAs-on-GaAlAs structures perform as well as GaAlAs-on-GaAs, fabricating low-resistance ohmic contacts to the electron gas, and achieving large conduction-band offsets. Alternatively, the GaInAs heterojunction system has few deep levels, high doping limits, large conduction band offsets, and high electron mobility and saturation drift velocity.

We have grown by MBE a transistor structure using a single quantum well of pseudomorphic GaInAs sandwiched between an undoped GaAs buffer layer and a doped GaAs capping layer. The structure starts with a mircometer-thick undoped GaAs buffer grown on a semi-insulating GaAs substrate. Next, 20–30 nm of $Ga_{0.85}In_{0.15}As$ is grown, followed by a GaAs spacer of 2–20 nm and then Si-doped GaAs with n = 2.8×10^{18} cm^{-3}. At 77 K, our highest mobility to date is 40,000 cm^2/W · s at a sheet carrier density of 6×10^{11} cm^{-2}. To our knowledge, this mobility is the highest yet reported for a strained-layer structure. We observe no persistent photoconductivity effect. In addition, magneto-transport measurements were made at 4.2 K which showed Shubnikov–de Haas oscillations characteristic of a 2-D electron gas. These measurements indicate a mobility in excess of 1000 000 cm^2/V · s at 4.2 K.

We have fabricated depletion-mode HEMT's from structures used for the transport measurements. For a gate length of 2 μm and a gate–source spacing of 4 μm we observe a g_m of 90 and 140 mS/mm at 300 and 77 K, respectively. These results are approximately two times that previously reported for modulation-doped GaInAs strained-layer superlattice structures and are comparable to electron-gas structures using modulation-doped lattice-matched AlInAs/GaInAs structures. For 1-μm gates we have observed a g_m of 176 mS/mm at room temperature, which, to our knowledge, is the highest value to date for a FET made of GaInAs.

VA-6 Temperature-Dependent Properties of the Double HBJT—S. Tiwari, S. L. Wright, and A. Kleinsasser, IBM Thomas J. Watson Research Center, Yorktown Heights, NY 10598.

We report on transport properties of the double heterojunction bipolar transistors (HBJT, GaAlAs/GaAs/GaAlAs) in the 4.2 to 350 K temperature range. Abrupt and graded junction devices made on conducting and semi-insulating substrates were studied. The devices fabricated showed current gains of 50–400 at room temperature for current densities of 1 to 10^5 A · cm^{-2}. The peripheral surface leakage current was small, resulting in current gains of 200 to 400 even for the smallest emitter area (approximately 2 μm square). These are the highest current densities and gains reported to date at these small dimensions. The devices tested had aluminum mole fractions of 0.25 to 0.30, base dopings ranging from 8×10^{17} cm^{-3} to 4×10^{18} cm^{-3}, base widths of 0.3 to 0.15 μm, and emitter and collector dopings of approximately 1×10^{17} cm^{-3}. In some of the devices, a base contact implant of magnesium followed by rapid thermal annealing was utilized. This resulted in a lowered external contact sheet resistance of 100 to 300 Ω as a function of dose. Magnesium was used because it shows anomalous diffusion only above the amorphization threshold of GaAs, and shows suppressed diffusion during rapid thermal annealing [1].

Transport for graded and upgraded devices in the 350 to 100 K temperature range is dominated by recombination in the base and in the depletion regions. The graded devices show a unity ideality factor for collected current as a function of injection, voltage, possibly corresponding to equilibrium drift-diffusion transport mechanism. The abrupt devices show similar behavior in this temperature range. The collector base junction (bottom junction) in abrupt devices shows a lower barrier than expected, perhaps due to grading of the junction caused by impurity or field enhanced intermixing. At temperatures near 100 K, the heterostructure discontinuities (intentional or unintentional) affect the current transport because discontinuities become much larger than the thermal voltage. In the case of the abrupt junction devices, charge storage at the collector base junction discontinuity and the resulting recombination causes an increase or decrease in the base current when the collector–base junction is forward or reverse biased. In the case of the graded junction devices this effect is negligible.

When the temperature is lowered further, current gains remain large. The injected current becomes dominated by tunneling through the barrier formed by the emitter–base conduction band discontinuity. The collected current is still exponential with the emitter–base voltage, but the exponent energy factor saturates. This is characterisitic of tunneling. At 4.2 K, steps in collected current as a function of base–emitter voltage are observed. We explain this as due to tunneling from GaAlAs into quantized GaAs conduction band states at the interface.

The negative resistance generally observed in the output characteristics of these devices is shown to be a consequence of tem-