devices that operate in the PDR region, such as the resonant-tunneling transistors and the QWITT oscillator. Reduced shot noise can lower the noise figure of amplifiers, narrow the linewidth of oscillators, and decrease the error rate in logic circuits.

In general, shot noise is characterized by the power spectral density $S_I = 2\Gamma e I_0$, where $I_0$ is the dc bias current and $\Gamma$ is the shot-noise factor. For single-barrier devices, $\Gamma = 1.0$. We have carried out shot-noise measurements to determine $\Gamma$ in three different RTD structures. The first is a GaAs/$Al_{0.42}Ga_{0.58}As$ RTD having a room-temperature peak current density $J_P$ and peak-to-valley current ratio (PVCR) of $1 \times 10^4$ A $cm^{-2}$ and 3.8, respectively. The remaining two are $In_{0.53}Ga_{0.47}As$/AlAs RTD's having a room-temperature $J_P$ of $3 \times 10^4$ and $2 \times 10^5$ A $\cdot$ $cm^{-2}$, and a PVCR of 12 and 5, respectively. In the PDR region, the noise spectral density was measured by radiometric techniques at a frequency of 1.0 GHz. This frequency was far above the $1/f$ knee and far below the $RC$ cutoff frequency. In all three devices, $\Gamma < 1.0$ in the PDR region below the current peak. The GaAs/AlGaAs and the high-$J_p$ InGaAs/AlAs RTD's displayed a minimum $\Gamma$ of approximately 0.45 at room temperature. The low-$J_p$ InGaAs/AlAs RTD displayed a minimum $\Gamma$ of 0.73 at room temperature. In the NDR region, the shot noise was determined indirectly from the phase-noise linewidth of the RTD operating as a microwave oscillator. At one point in the NDR region of the GaAs/AlGaAs RTD, $\Gamma \approx 5$ was measured at room temperature. In spite of this fact, the linewidth of the RTD oscillator at a given frequency is less than that of a Gunn-diode oscillator and much less than that of an IMPATT-diode oscillator.

The deviations from $\Gamma = 1.0$ occur because the resonant-tunneling current in a double-barrier structure is self-modulated. By this mechanism, sheet charge accumulates in the quantum well in proportion ot the current density. The sheet charge affects the potential across the double-barrier structure and shifts the transmission function, thereby modulating the RTD current. A theoretical model will be presented that agrees with the experimentally observed short-noise effects, and predicts that RTD's can be designed with further reduced $\Gamma$ in the PDR region. This is the first study of microwave shot noise in RTD's.

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**VB-4 RF Response of High RF-$T_C$ SNS Josephson Microbridges Suitable for Integrated Circuit Applications**—R. H. Ono, J. A. Beall, M. W. Cromar, T. E. Harvey, M. E. Johansson, C. D. Reintsema, and D. A. Rudman, Electromagnetic Technology Division, National Institute of Standards and Technology, Boulder, CO 80303.

We have developed a simple process for microfabricating high transition temperature superconductor-normal metal-superconductor (SNS) Josephson devices which operate up to 80 K, and are reasonably ideal at 43 K. Bridge resistances greater than 10 Ω and critical current-normal state resistance ($I_CR_N$) products greater than 1 mV have been achieved. Clearly defined RF steps have been observed, with power dependence qualitatively similar to theoretical predictions. The fabrication process and the device characteristics are suitable for superconducting integrated circuit applications such as millimeter-wave Josephson oscillators, parametric amplifiers, and single-flux quantum digital logic.

We have used a step-edge technique with *in situ* deposition of both the superconductor and normal metal to make very short SNS microbridges. The superconductor, $YBa_2Cu_3O_{7-\delta}$, is deposited by pulsed laser ablation at an angle onto a substrate which has a nearly vertical step, allowing shadowing from the step edge to create a break in the superconductor. The normal metal is then deposited from the other direction so as to cover the step and bridge the superconducting banks. The length of the bridge is defined by the step height and thus can be made very short. To ensure the lowest possible contact resitance between the superconducting and normal metal films, we deposit the normal metal without exposure to air (*in situ*). This technique also allows the normal metal to contact the exposed edges of the *c*-axis-oriented films, producing a low boundary resistance *a-b* plane contact. Once the YBCO-normal metal bilayer is completed, the lateral device dimensions are patterned using a positive photoresist and ion milling.

We have used both pure Ag and a Ag-Au alloy as the normal metal link. The alloy typically had a low-temperature resistivity 5-10 times higher than the pure noble metal. The resistances of the Ag bridges were typically 1 Ω or less, whereas those of the alloy bridges were usually over 10 Ω. As predicted by boundary conditions from the standard SNS model [1], the high-resistance alloy bridges showed a higher $I_CR_N$ than the pure Ag bridges.

The voltage-current ($V$-$I$) characteristics of these devices are similar to those predicted by the resistively shunted junction (RSJ) model [2], as opposed to the rounded, nonlinear $V$-$I$ curve due to flux flow resistance. We also observe RF-induced steps at voltages of $nh\nu/2e$ to beyond $n = 20$, even at 43 K, and steps are still clearly defined at 78 K. The amplitude of the step size modulates with increasing RF power, as predicted by the RSJ model. The RF power modulates the zeroth and first steps over more than six periods, with the interval between zeros found to agree with RSJ-based predictions [3] within a factor of 2.

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**VIA-1 Effects of Substrate Tilting in Substantial Improvement of DC Performance of AlGaAs/GaAs n-p-n DHBT's Grown by MBE**—Naresh Chand, Paul R. Berger, and Niloy K. Dutta, AT&T Bell Laboratories, Murray Hill, NJ 07974.

We observe a marked improvement in the dc performance of $Al_{0.5}Ga_{0.5}As$/GaAs/$Al_{0.5}Ga_{0.5}As$ double heterojunction bipolar transistors (DHBT's) by tilting the (100) GaAs substrates 3° towards ⟨111⟩A. On the tilted substrate, the surface, space charge and bulk recombination currents are reduced, and the quality of AlGaAs/GaAs heterointerfaces is improved. As a result, both the emitter injection efficiency ($\eta$) and base transport factor are increased leading to a substantial increase in current gain with a marked reduction of its current and junction geometry dependence, as shown in Table I.

The structures studied were grown simultaneously at 580°C on Si-doped $n^+$-GaAs flat (100) and misoriented substrates. A compositional grading of 300 Å was employed at the emitter-base (e-b) junction. The base-collector (b-c) junction was not graded to see the effect of an abrupt junction on the offset voltage and gain. The

TABLE I
JUNCTION GEOMETRY DEPENDENCE OF CURRENT GAIN IN AlGaAs/GaAs n-p-n DHBT's GROWN ON (100) AND 3° OFF (100) TOWARDS ⟨111⟩ A GaAs SUBSTRATES

| Emitter–Base Junction Area ($\mu$m × $\mu$m) | Substrate: Tilted $J_C$ (kA · cm$^{-2}$) | Tilted $\beta_{max}$ | Substrate: Flat $J_C$ (kA · cm$^{-2}$) | Flat $\beta_{max}$ |
|---|---|---|---|---|
| 50 × 50 | 2.6 | 1200 | 2.3 | 675 |
| 28 × 28 | 5.9 | 1410 | 4.1 | 675 |
| 10 × 40 | 6.0 | 1630 | 7.0 | 725 |
| (10×)* 5 × 25 | 2.6 | 1060 | 2.2 | 210 |
| (5×)* 4 × 20 | 9.3 | 1000 | 8.5 | 124 |
| (2×)* 4 × 20 | 8.8 | 620 | 17.5 | 105 |
| 5 × 20 | 9.0 | 515 | 12.0 | 150 |

*No of emitter fingers.

GaAs base thickness ($W_B$) was 1000 Å of which 800 Å in the middle was doped with Be ($5 \times 10^{18}$ cm$^{-3}$) and 100 Å on each side was undoped. We have used a higher AlAs content $x$ of 0.5 in both emitter and collector, which is desirable for the device also to be used as a laser in OEIC's, for increasing gain and collector breakdown voltage, and for reducing the collector leakage current and temperature sensitivity of the device.

The device characteristics and current gain changed very little between 25 and 100°C on both substrates. However, for a given $I_C$ the gain was significantly larger on the tilted substrate but the difference in gain decreased with increasing $I_C$. Assuming $\eta = 1$, $W_B = 0.08$ $\mu$m, and an electron diffusion length ($L_n$) = 2 $\mu$m for $p = 5 \times 10^{18}$ cm$^{-3}$ in base, we expect a $\beta_{max}$ of 1250. Our actual $W_B = 0.1$ $\mu$m and a $\beta_{max} = 1630$ suggest $L_n$ to be higher than 2 $\mu$m, and thus the bulk recombination is reduced in the base on the tilted substrate, despite the abrupt b-c junction. In fact, on a tilted GaAs substrate an $Al_{0.25}Ga_{.75}As$ base DHBT also exhibit a current gain as high as 400. The abrupt b-c junction did not result in an offset voltage but reduced the carrier collection efficiency in the region where the b-c junciton is forward biased, i.e., for lower values of $V_{CE}$.

The improved bulk and interfacial quality of AlGaAs/GaAs heterostructures on the misoriented substrates is confirmed by TEM cross sections and SIMS measurements, and is due largely to lower affinity of Ga-like surface steps for defects and impurity incorporation. This reduces the bulk and space-change recombination currents. Also, inactivity of Ga-like steps reduces surface recombination of carriers. Detailed results of the study and their explanations will be presented.

**VIA-2 Molecular Beam Epitaxial GaAs/$Al_{0.2}Ga_{0.8}$As Heterojunction Bipolar Transistor on (311)A GaAs Substrate With All-Silicon Doping**—W. Q. Li and P. Bhattacharya, Center for High Frequency Microelectronics, Department of Electrical Engineering and Computer Science, The University of Michigan, Ann Arbor, MI 48109-2122.

Beryllium (Be) is commonly used as the p-type dopant during molecular beam epitaxy (MBE) GaAs and other III–V compounds due to its favorable vapor pressure. It is therefore the dopant of choice for the base region of n-p-n transistors. Unfortunately, Be diffusion during growth and post-growth processing [1] and even during operation results in degradation of device performance. Other dopant species such as C are being investigated. Silicon, which is an amphoteric dopant in GaAs, is much less diffusive, Si-doping in (100)-oriented crystals produces well-behaved n-type materials under normal MBE conditions, but can produce n- or p-type layers on higher index planes, depending on the growth parameters [2]. We have therefore investigated the characteristics and reliability of p-doping in GaAs with Si by MBE and have realized, for the first time, high gain n-p-n GaAs/AlGaAs heterojunction bipolar transistors (HBT) on (311)A GaAs substrates by all-silicon doping.

The (311) GaAs surface consists of equal numbers of single and double dangling bond sites. Therefore, Si atoms have an equal opportunity to incorporate As or Ga sites. On the (311)A GaAs surface, Si predominantly incorporates as a p-type dopant. However, if the substrate temperature is lower than 450°C and the V/III flux ration is higher than 3, Si doping produces n-type GaAs or AlGaAs.

To realize the HBT, a 0.5-$\mu$m-thick GaAs layer ($n = 5 \times 10^{18}$ cm$^{-3}$) was first grown at 450°C with V/III flux ratio of 4, followed by 0.3-$\mu$m-thick undoped GaAs collector grown at 610°C to ensure p-type conductivity. The growth temperature was then lowered to 450° and the V/III was increased to 4 before growing the 0.1 $\mu$m $Al_{0.2}Ga_{0.8}As$ emitter ($n = 5 \times 10^{17}$ cm$^{-3}$). Finally, a 0.2-$\mu$m GaAs ($n = 5 \times 10^{18}$ cm$^{-3}$) contact layer was grown under the same conditions. Note that Si is the single dopant specie throughout the growth. The capacitance–voltage profile of the heterostructure indicates sharp emitter–base and base–collector junctions and a base doping level of $p = 1.6 \times 10^{18}$ cm$^{-3}$. A secondary-ion mass spectroscopy (SIMS) of a p-type Si-doped 0.1-$\mu$m GaAs layer doped to the same level as the base region indicates very small Si diffusion, and on comparison with the $C$–$V$ data, it is clear that under the specific growth conditions Si predominantly incorporates as a p-type dopant with little compensation.

Transistor made of the heterostructure having 30 × 35 $\mu$m$^2$ emitter region show common emitter current gains of 80–100 at room temperature. The gain is very uniform as the current level increases, indicating that the base recombination is very small. The emitter–base junction exhibits excellent current–voltage characteristics with sharp forward turn-on and very small reverse leakage current (6 nA at −5V). This is also confirmed by the Gummel plot which shows an ideality factor of 1.05. These preliminary results are very encouraging and device performance could be further improved with optimized design. This work is in progress together with microwave measurements on the devices.

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**VIA-3 Reduction of Low-Frequency Noise in n-p-n AlGaAs/GaAs HBT's**—Damian Costa, William U. Liu, and James S. Harris, Jr., 226 McCullough Building, Stanford University, Stanford, CA 94305.

While the high-frequency performance of AlGaAs/GaAs HBT's is well-established [1], the noise characteristics of HBT's have received little attention. Recent experimental results [2] indicated that an HBT incorporating a thin depleted AlGaAs layer (AlGaAs ledge)