sibility of collision free transport that can lead to ultrafast devices. We have fabricated the *first* $In_yGa_{1-y}As/In_xAl_{1-x}As$ hot-electron transistor and obtained evidence for the existence of ballastic transport in the InGaAs base layer at 77 K as opposed to 4 K solely used for GaAs/AlGaAs system.

Hot-electron transistors were fabricated using i-$In_xAl_{1-x}As$ barriers and n^+-$In_yGa_{1-y}As$ for the base which were grown by molecular-beam epitaxy on InP substrates. Electrons tunneling through a 75-Å-thick i-InAlAs emitter barrier enter the n^+-InGaAs base region as hot electrons with energies close to the emitter–base bias potential. Some of these hot electrons traverse the InGaAs base plus the InAlAs collector barrier without any scattering and are collected by the negatively biased collector. Using this negatively biased collector as the electron energy selector, we have determined the energy distribution of the hot electrons at 77 K. In order to determine the fraction of electrons ballistically traversing the base and the collector barrier we measured the gain at collector voltages corresponding to the ballistic peak in output conductance. The percentage of ballistic electrons increased from 1.6 to as high as 23 percent when the InGaAs base layer thickness was decreased from 3000 to 1000 Å and the InAlAs collector barrier thickness from 800 to 500 Å. The effective electron mean free path in the devices with 1000-Å base was 1020 Å compared to 920 Å in the device with 3000-Å base probably indicating better material quality. The collector barrier heights measured (633 meV) are in reasonable agreement with those deduced independently from thermionic emission studies in SIS structures. Details of the device fabrication and analysis as well as the determination of the conduction band edge discontinuity from HET's and SIS diodes will be described.

VIB-6 Perpendicular Transport Measurements in GaAs/(Al,Ga)As/GaAs Heterostructures—P. M. Solomon and S. L. Wright, IBM T. J. Watson Research Center, Yorktown Heights, NY.

We have examined the temperature dependence of the current-voltage characteristics of n^+-GaAs/i-(Al,Ga)As/n^-GaAs barrier structures in both the thermionic and thermionic-field emission regimes. These structures had Al mole fractions between 0.40 and 0.60, with a barrier thickness of 300 Å. This range of barrier compositions is interesting because we expect to see a change over from the direct (Γ) to the indirect (X) conduction band in (Al,Ga)As. We have measured the activation energy for electron transport from the n^+-GaAs layer through the (Al,Ga)As layer by analysis of the experimental data with standard thermionic emission theory. The largest uncertainty in inferring the heterojunction discontinuities from these data ($\simeq$30 mV) is accounting for the position of the Fermi level in the GaAs near the interface, C–V measurements indicated that charge in the (Al,Ga)As was not large enough to effect the barrier by more than $\simeq$10 mV. The conduction band discontinuity increased from 350 mV at 40-percent Al to almost 400 mV at 50-percent Al, and then decreased to 320 mV at 60-percent Al. The peak value is significantly higher than the maximum value which had been previously predicted [1]. These results also suggest that the direct/indirect cross-over for electron transport occurs at an Al mole fraction close to 50 percent, much higher than the cross-over composition determined from optical data ($\simeq$40 percent) on well-characterized bulk (Al,Ga)As material.

Tunneling currents from the n^- layer through the barrier were measured over a temperature range of 79–130 K and at voltages greater than the barrier height. The electric field at the injecting interface was calculated by integrating the C–V curves from the flat-band voltage. The results were analyzed assuming standard thermionic-field emission theory, using numerical integration over energy. The Fermi level in the accumulation layer was calculated using a field dependence based on Stern and Das Sarma [2]. The temperature dependence of the current allows us to separate the effects of tunneling effective mass and barrier height. The conduction band discontinuities derived from tunneling tracked those derived from thermionic emission, indicating that the same energy band is involved in both processes. The tunneling effective masses were low: $\simeq$0.07 and 0.12 for (Al,Ga)As barriers with 40- and 60-percent Al. These results can not be explained by tunneling through the longitudinal X valley since the effective mass there is very large. It is likely that the transverse X valleys are involved in the tunneling process along with some mechanism for momentum transfer.

[1] J. Batey and S. L. Wright, *J. Appl. Phys.*, vol. 59, p. 200, 1986.
[2] F. Stern and S. Das Sarma, *Phys. Rev. B*, vol. 30, p. 840, 1984.

VIB-7 Improved Physics of Ohmic Contacts to Semiconductors*—K. Shenai, R. W. Dutton, and S. J. Eglash,** Integrated Circuits Lab., Stanford University, Stanford, CA 94305.

This work presents a systematic study of both theoretical and experimental aspects of carrier transport in metal–semiconductor junctions in order to understand the ohmic behavior of these interfaces. Experimental results obtained from contact structures grown by MBE are in excellent agreement with a novel transport theory which uses a three-layer approximation for the metal-semiconductor interface and satisfies both charge conservation and quantum effects at the interface. The specific contact resistance R_c calculated from the new theory is nearly two orders of magnitude smaller compared to existing contact resistance calculations, and is in excellent agreement with the measured contact resistance of nonalloyed contacts deposited on heavily Sn-doped n^+ GaAs layers grown by MBE. The measured contact resistance of nonalloyed contacts fabricated is $2 \times 10^{-7}\ \Omega \cdot cm^2$, and is among the lowest reported in the literature for any type of contact.

In order to understand the ohmic behavior of metal–semiconductor junctions, a detailed study of the Schottky-barrier formation and transport properties is required. Most studies of ohmic contacts are based on the theory presented by Chang *et al.* [1]. However, a number of key physical mechanisms are not included in this theory which have been found to be crucial in understanding the transport properties, especially in determining the specific contact resistance R_c of ohmic contacts.

This investigation deals with both theoretical and experimental aspects of ohmic contact formation in semiconductors. The theoretical model includes both thermionic-field emission and tunneling currents determined from an accurate barrier potential calculated in the presence of various sources of interface charge. The barrier model includes 1) the penetration of metallic wave functions into the semiconductor energy gap, 2) localized defect states, 3) a two-band model for electronic states in the semiconductor energy gap, 4) high-field effects on the carrier statistics in satellite valleys, and 5) contribution of free charge to the space-charge potential. The tunneling calculations utilize an improved formulation for carrier potential energy and account for a finite charge at the interface. The experimental results are obtained from nonalloyed contacts deposited on GaAs layers grown by MBE.

The nonalloyed ohmic contacts are fabricated from heavily Sn-doped n^+ GaAs grown by MBE with a donor density of $\simeq 2 \times 10^{19}$ cm^{-3} measured using SIMS and Hall techniques. A layer of pure Sn is deposited in the MBE system prior to the growth of n^+ GaAs layer in order to reduce Sn accumulation at the surface. The room-temperature-measured specific contact resistance of these nonalloyed ohmic contacts is $\simeq 2 \times 10^{-7}\ \Omega \cdot cm^2$. The measured specific contact resistance is in excellent agreement with the new theoretical model at a number of temperatures, and is nearly two orders of magnitude smaller than that predicted from the theory of Change *et al.* (i.e., $R_c = 3 \times 10^{-5}\ \Omega \cdot cm^2$ for the same material parameters). The dominant effects are the dipole barrier lowering and the two band formulation of electronic states in the semiconductor energy gap. The statistics of measured parameters obtained from con-