ULTRAHIGH-SPEED BIPOLAR TRANSISTORS

Understanding nonequilibrium electron transport in III–V compound semiconductors has helped in the development of the fastest bipolar transistors.

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The invention of the transistor in the late 1940s has had tremendous technological ramifications, heralding as it did an era of semiconductor microelectronics.[1] At the heart of the transistor's device applications are its ability to amplify and the ease with which it can be fabricated in very complex integrated circuits.

The physics underlying the transistor's gain involves the diffusive motion of charge carriers through semiconducting materials. Figure 2b shows the band edge profile of an npn transistor not dissimilar to the first one invented. The emitter–base junction is under a forward bias, so there is a net flow of conduction-band electrons into the p-type base. In a high-quality transistor these electrons diffuse across the base, drift and diffuse in the accelerating electric field of the reverse-biased base–collector junction and ultimately flow as collector current I_C. The current gain of such a transistor is limited by back injection of valence-band charge carriers from the p-type base and their subsequent recombination in the n-type emitter. This back injection of holes gives rise to a base current I_B. If the base current is small compared with the collector current, then a modest change ΔI_B in its value can cause a large change ΔI_C in collector current, resulting in a large current gain β, defined as $\Delta I_C/\Delta I_B$.

A device design that gives better gain and response time makes use of a wide-bandgap emitter to form a heterostructure bipolar transistor. The term "heterostructure" was introduced by Izuo Hayashi and Morton Panish to describe the structure of injection lasers having lattice-matched and "defect free" interfaces between different semiconductor materials. The heterostructure bipolar transistor concept was first proposed by William Shockley and later developed theoretically by Herbert Kroemer.[2] In such a structure (see figure 3) there is a potential barrier in the valence band that suppresses the back injection of holes and can therefore increase the current gain. At the same time, transport of conduction-band electrons injected into the base may be improved by, for example, launching charge carriers with some excess kinetic energy. In recent years Peter Asbeck and his coworkers at Rockwell International and Tadao Ishibashi and his coworkers at NTT in Japan have developed such transistors by using a wide-bandgap AlGaAs emitter and a narrower-bandgap GaAs base and collector to form a AlGaAs/GaAs heterostructure bipolar transistor.[3] This effort has resulted in production of the highest-speed small-scale functional digital integrated circuits. At first glance these results suggest the emergence of a new heterostructure bipolar transistor technology that ultimately could be used to make faster computers and other equipment. However, the low diffusion velocities (about 10^7 cm/sec) and the small number of bipolar transistors that can be integrated into one circuit (less than 10 000) severely restrict potential applications.

Device speed would increase significantly if electrons moved more quickly from emitter to collector. In fact, early on in the development of transistors it was realized that, at least in principle, extreme nonequilibrium transport—so-called ballistic transport—could result in elec-

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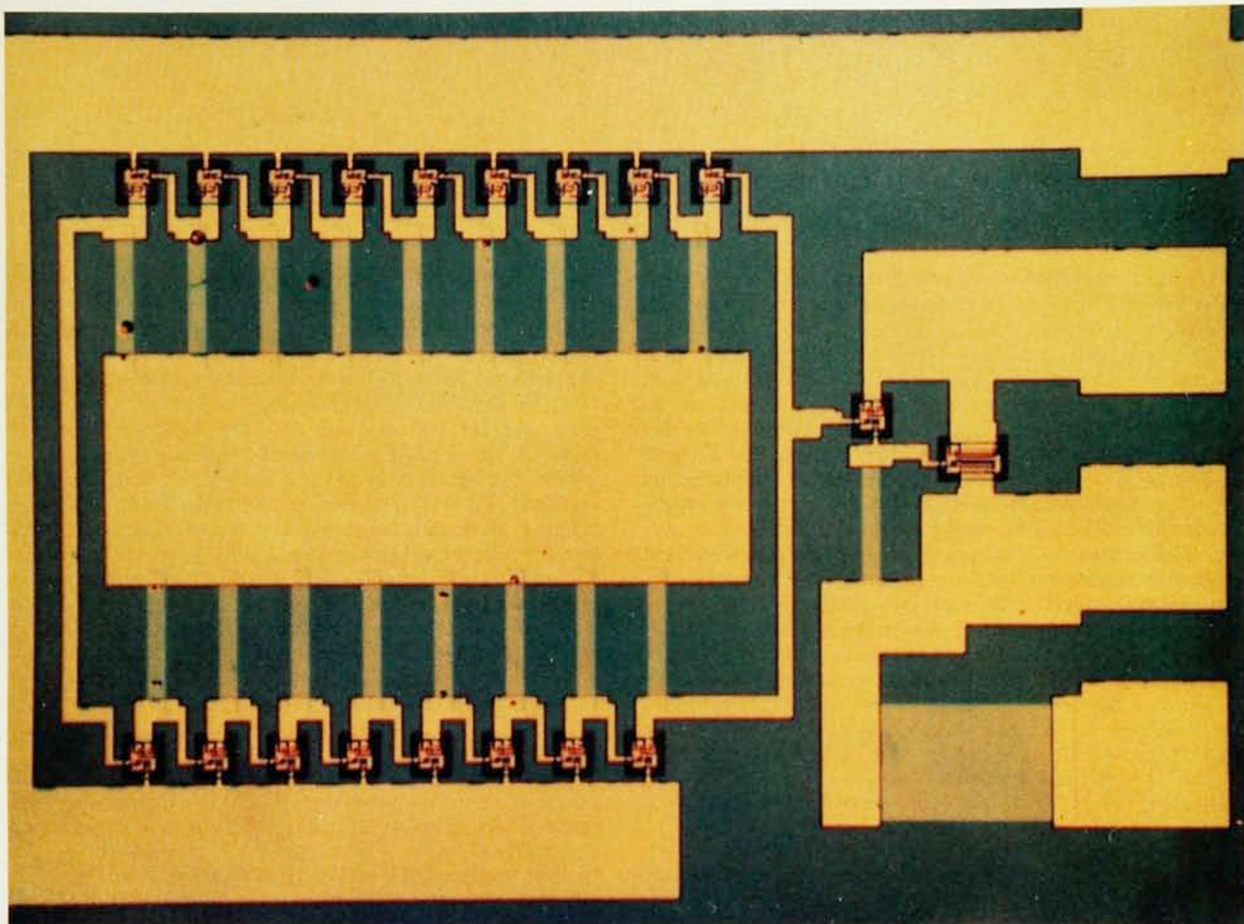


Ring oscillator that makes use of $InP/In_{0.53}Ga_{0.47}As$ heterostructure bipolar transistors. This 17-stage logic circuit has a propagation delay of 14.3 picoseconds per gate. **Figure 1**

tron velocities of around 10^8 cm/sec and, therefore, potentially much faster devices.[2] It is only recently, however, that improvements in crystal growth have allowed physicists to verify experimentally the existence of ballistic transport in III–V compound semiconductors and to apply the knowledge gleaned from these studies to fabricate new, very fast devices. These studies indicate that $InP/In_{0.53}Ga_{0.47}As$ is the best available material system with which to exploit ballistic electron transport and fabricate fast integrated circuits such as the one shown above. Our heterostructure bipolar transistors are characterized by a subpicosecond temporal response and are the fastest devices of their kind. The development of these devices is the subject of this article.

As discussed below, the physics underlying the operation of these transistors is qualitatively different from that of the original diffusive device. On its own, this fact raises new questions concerning the details of device operation that lie outside the range of conventional semiclassical theories.[4] The answers to these questions require a quantum mechanical description of the transistor. Efforts to extend the limits of high-performance transistors have exposed significant deficiencies in our present understanding of nonequilibrium electron transport phenomena in semiconductors. Phenomena important to high-speed transistors are also discussed in Karl Hess's article (page 34), and the measurement of scattering times that are relevant for the design of such transistors is also discussed in David Auston's article (page 46).

Design considerations

To make a transistor that utilizes nonequilibrium transport, it is necessary, of course, to have a source of high-velocity electrons. In semiconductors, this is readily achieved by accelerating electrons in the electric field generated by a heterojunction. For example, the junction between InP grown on $In_{0.53}Ga_{0.47}As$ results in a conduction-band discontinuity of almost 300 meV.

To illustrate how this effect may be applied to a transistor, consider the band diagram for an npn heterostructure bipolar transistor shown schematically in figure 3. A bias voltage V_{BE} applied between the base and the oemitter causes electrons to flow across the abrupt emitter–base junction. Electrons enter the base with a high velocity—around 10^8 cm/sec—and a large component of momentum perpendicular to the heterojunction (in the z direction). The angular spread of such an injected beam of energy E is only 16°; it is given approximately by $\tan^{-1}(kT/E)^{1/2}$, where kT, the ambient thermal energy at room temperature, is 25 meV. Thus, in the absence of scattering, one need consider only current flow in the z direction, and the electron's high velocity results in a very short transit time across the base and collector space-charge region.

In reality, however, the situation is complicated by

the finite probability of elecorons scattering either elastically or inelastically, and thereby slowing average motion in the z direction. Associated with such scattering processes is a characteristic mean free path λ. Clearly, if we are to make use of nonequilibrium electron transport we need to be concerned with optimizing conditions to ensure that the mean free path is greater than either the base or collector space-charge-region thickness (Z_B and Z_C, respectively). This optimization can be achieved by using a combination of correct choice of materials, reduction of Z_B and Z_C, and high doping levels.

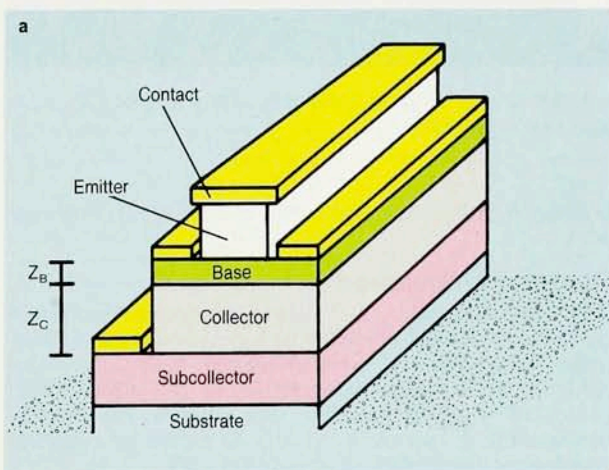
The operation of nonequilibrium electron transport devices is qualitatively different from that of conventional transistors, which make use of relatively low-velocity diffusive electron transport. A bipolar transistor typically works by transforming a low-impedance current source, the emitter, into a high-impedance current source, the collector. Electrons injected from the forward-biased emitter–base diode traverse the base and are accelerated in the electric field of the reverse-biased base–collector diode. Irreversible scattering processes, such as phonon emission, occur in the collector depletion region. As a result the electron loses energy, remaining close in energy to the conduction-band minimum, and reverse current flow against the electric field in the depletion region is small. In this way, the transformation to high impedance occurs over the length of the collector depletion region.

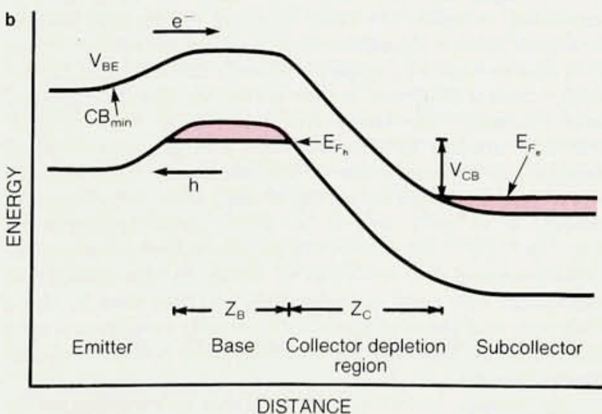
The situation is different for a transistor in which at least part of the current flow through the base and collector takes place via coherent ballistic transport, for which the mean free path λ is greater than the total thickness $Z_B + Z_C$ of the base and collector space-charge regions. In such a transistor the impedance transformation for coherent electrons takes place by scattering in the degenerate n^+ subcollector, which is a heavily doped material that serves as the collector contact. In principle, coherent electron transport through the base and collector of a ballistic transistor can influence the emitter current and thereby change the fundamental impedance-transforming properties of the transistor.

Crystal growth

The ability to fabricate a structure such as that illustrated in figure 3 requires precision epitaxial growth of appropriately doped layers of $In_{0.53}Ga_{0.47}As$ and InP. The $In_{0.53}Ga_{0.47}As$ emitter and subcollector contact layers must be heavily n-type (about 10^{20} free electrons/cm^3) to keep parasitic resistances as small as possible, and as discussed below, the $In_{0.53}Ga_{0.47}As$ base should be strongly p-type (also about 10^{20} free holes/cm^3). The emitter–base heterojunction must be abrupt—on an atomic layer scale—while the doping transition from the wide-bandgap n-type InP emitter, doped at about 10^{18}/cm^3, to the p-type base must be accomplished within 50 Å of the heterojunction. All the above has to be achieved while maintaining a high-quality semiconductor material.

These challenging demands have been met by using a

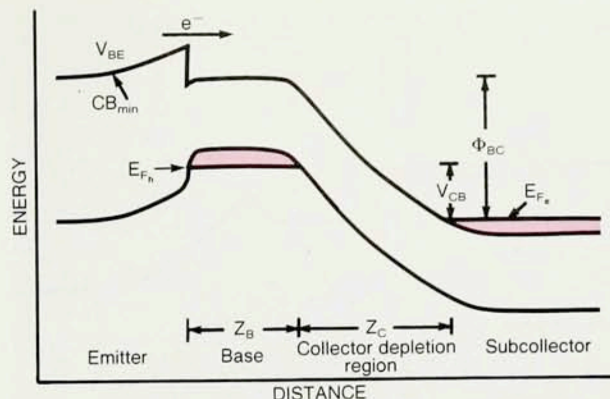




Bipolar transistor scheme (**a**) and band edge profile when the device is under bias (**b**). The n-type emitter injects conduction-band electrons into the p-type base. The back injection of holes (h) from the valence band in the base and their recombination in the n-type emitter gives rise to a base current I_B. If the base current is small, then most conduction-band electrons can diffuse from the emitter, cross the base and flow as collector current I_C. In this situation, small variations in base current cause large changes in collector current, and the transistor's current gain is large. The base and collector are of thickness Z_B and Z_C, respectively. The base–emitter bias is V_{BE} and the collector–base bias is V_{CB}. Also indicated are the conduction-band minimum CB_{min}, the Fermi energy E_{F_h} of holes in the valence band and the Fermi energy E_{F_e} of electrons in the conduction band. **Figure 2**

hydride-source molecular-beam epitaxy technique.[5] This is a vacuum thin-film growth method in which beams of Ga and In from evaporative or effusion sources and beams of As_2 and P_2 molecules from the decomposition of AsH_3 and PH_3 impinge on a heated InP substrate. Effusion sources are used for the p-type dopant element Be and the n-type dopant element Sn.

The growth temperature is dictated by the need to limit Be diffusion in the crystal and by a compromise between the requirements for high surface mobility of the major components to ensure smooth, layer-by-layer growth and for low mobility of Be to prevent its precipitation. High-quality devices, described below, are grown at about 425–450 °C with a base doping of $1\times10^{20}/cm^3$. We have little doubt that such device structures can be grown with other epitaxy methods once the necessary p-type carrier concentrations in the base and contact layers are established.



Heterostructure bipolar transistor band edge profile when the device is under bias. A wide-bandgap n-type emitter injects electrons with excess kinetic energy into the p-type base region. A potential barrier in the valence band suppresses the back injection of holes. The total potential drop in the collector is Φ_{BC}; the other symbols are defined in the caption to figure 2. **Figure 3**

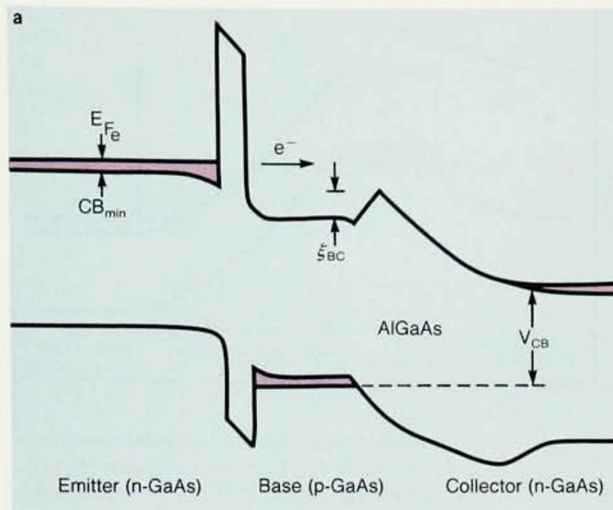
Base transport

When the mean free path is greater than the thickness Z_B of the base space-charge region, one expects a significant number of electrons to traverse the base without scattering. This has been verified experimentally using a technique called hot-electron spectroscopy,[6] which is also discussed in Hess's article (page 34). Figure 4a is an energy-band diagram for an npn transistor with conduction-band electrons that are tunnel injected into the base with excess kinetic energy. The p-type GaAs base has a relatively low impurity concentration of $3\times10^{18}/cm^3$ and a thickness Z_B of 260 Å. Because the energy ξ_{BC} of the AlGaAs collector barrier may be varied by changing the base–collector bias V_{CB}, recording the derivative of the collector current, dI_C/dV_{CB}, together with the corresponding values of V_{CB} is a way of measuring the projection of the nonequilibrium electron momentum distribution perpendicular to the collector barrier. The measured derivative data in figure 4b are for excess kinetic energies of 220 meV (upper curve) and 170 meV (lower curve). The peak at $V_{CB}\sim-1$ V is due to electrons with excess kinetic energy traversing the base ballistically (without scattering), while the feature near $+1$ V is from electrons that have suffered elastic and inelastic collisions. Figure 4c shows results of numerical simulations.[6] The overall agreement between experiment and calculation gives one confidence that the methods used to evaluate scattering rates are reasonably accurate. Differences such as experimentally unresolved spectral features may be explained by limits on spectrometer resolution. Typical mean free paths for nonequilibrium electrons are 300 Å in p-type GaAs and 600 Å in $In_{0.53}Ga_{0.47}As$.

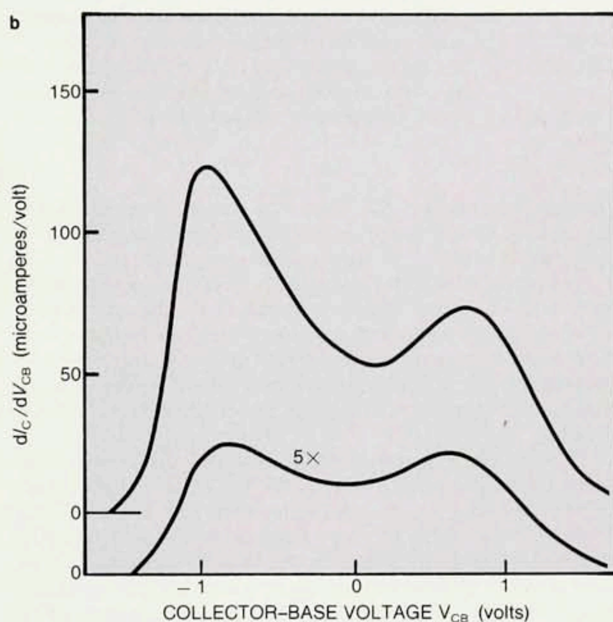
Because we require the mean free path to be greater than the thickness Z_B of the base space-charge region, we might think simple reduction of Z_B would result in extreme nonequilibrium transport in a heterostructure bipolar transistor, and hence a faster device. Unfortunately, one must consider resistance and capacitance effects—*RC* time constants. In a useful device, a reduction in Z_B requires an increase in the majority charge-carrier (hole) density in the base to keep the base resistance small, thereby minimizing *RC* time constants. For example, $In_{0.53}Ga_{0.47}As$ with a doping of $5\times10^{20}/cm^3$ has a mobility of 20 $cm^2\,V^{-1}\,sec^{-1}$, so that a sheet resistance under 200 Ω/□ requires a base space-charge region thickness greater than 300 Å. (The sheet resistance is the resistance between opposite edges of a square, which is independent of the size of the square.) Obviously, it is important to understand the influence that increasing the density of p-type carriers has on nonequilibrium electron transport in the base.

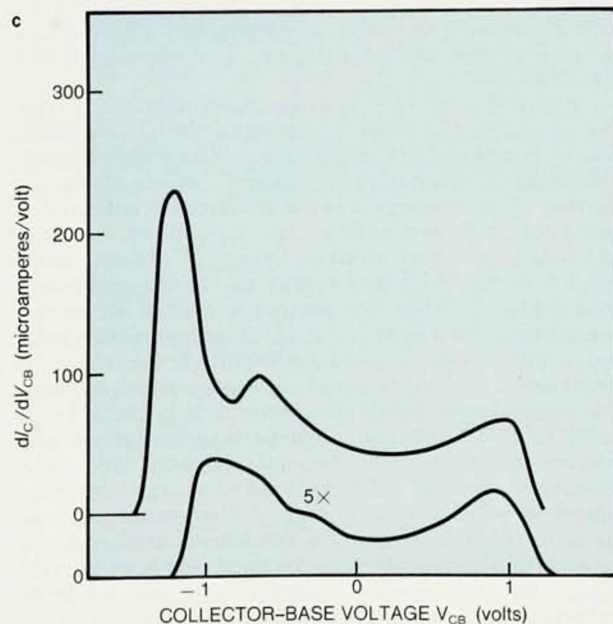
A conduction-band electron injected into the p-type base with excess kinetic energy E may scatter inelastically, losing energy $\hbar\omega$ and changing momentum by $\mathbf{q}$. The electron may also scatter elastically from statically screened ionized impurities in the base. In general, there are a number of different inelastic scattering processes, or "channels," by which an electron may lose energy. For example, an important energy-loss channel for nonequilibrium electrons in the polar semiconductors of interest to us is scattering off longitudinal optic-phonon lattice vibrations.

If a conduction-band electron is injected into a p-type semiconductor, the number of possible energy-loss channels increases and the situation gets fairly complicated. This point is illustrated in figure 5, which shows an electron of initial energy E in the conduction band (band 3) losing energy $\hbar\omega$ and undergoing a momentum change $\mathbf{q}$ by exciting a valence electron from the light-hole band (band 2) across the Fermi energy E_{F_h} to the heavy-hole band (band 1). When the electron is excited across the Fermi energy from band 2 to band 1 it leaves behind a hole, and so this process is called single-particle electron–hole pair creation. From the figure one can see that up to four new energy-loss channels are opened: 2 to 1, 2 to 2, 1 to 2 and 1 to 1. In addition, single-particle excitations can interact, coupling with the optic phonons and with themselves, to form different types of energy-loss channels. Instead of describing each of these processes, it is easier to think in terms of a continuous mathematical function that measures the scattering strength, or spectral weight, for each possible energy loss $\hbar\omega$ and scattered wavevector $\mathbf{q}$. A convenient way to do this is to use an ap-



Characteristics of a III–V bipolar transistor with a tunnel emitter. **a:** Energy-band profile. The collector barrier energy is ξ_{BC}. **b:** Derivative of the collector current with respect to collector–base voltage, dI_C/dV_{CB}, versus V_{CB}. The lower curve (plotted at five times its actual height, with an offset origin) is for an injection energy of 170 meV. The upper curve is for an injection energy of 220 meV. The measurements were made at 4.2 K. **c:** Numerical simulation of the spectra shown in **b**. (Adapted from ref. 6.) **Figure 4**





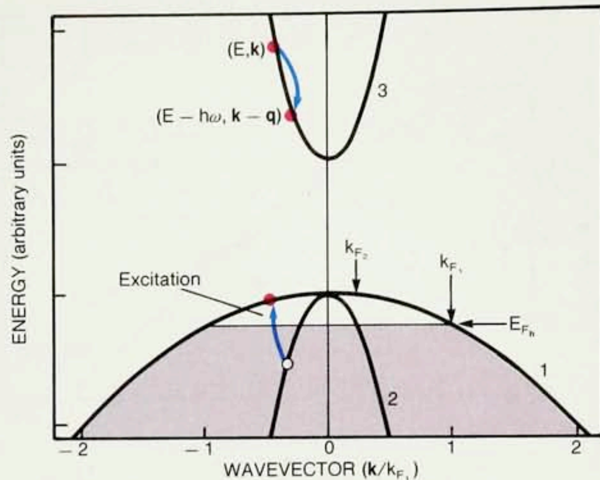
propriate dielectric response function $\epsilon(\mathbf{q},\omega)$, which describes the coupled majority-carrier and longitudinal optic-phonon excitations in the p-type base.

To calculate the total inelastic scattering rate $1/\tau_{in}$ for a fixed injection energy, we must integrate the spectral weight, $-\operatorname{Im}\epsilon(\mathbf{q},\omega)$, over all possible energy losses $\hbar\omega$ and momentum changes $\mathbf{q}$. Of course, energy and momentum conservation (in the limit $T=0$ K) limit the number and type, or phase space, of energy-loss processes that can occur. As a result, for a fixed electron injection energy, the inelastic scattering rate can actually decrease for large concentrations of p-type carriers. Put simply, energy and momentum conservation dictate that some loss channels become inaccessible and that in other channels only restricted types and numbers of loss processes can occur. Thus as carrier concentration rises, the inelastic scattering rate increases, reaches a maximum and then decreases. As figure 6 shows, for an injection energy of 300 meV in $In_{0.53}Ga_{0.47}As$, the inelastic scattering rate reaches a maximum at a carrier concentration around $5\times10^{19}/cm^3$ and then decreases to almost one-eighth the maximum at $10^{21}/cm^3$. A surprising conclusion emerges, namely, that very large carrier concentrations can actually reduce inelastic scattering rates for nonequilibrium electrons in the base.[7] Therefore, ballistic transport in the base of an npn transistor can be enhanced by using very high p-type doping levels.

For the sake of clarity, in the above discussion we adopted the low-temperature limit. However, similar results apply at room temperature, the only significant difference being a modest 30% increase in the inelastic scattering rate.

Collector transport

After traversing the base, the injected electrons impinge on the base–collector junction. The electrons that arrive at this junction have a momentum distribution that reflects the elastic and inelastic scattering events that occurred while they were transiting the base. These electrons are then accelerated and gain kinetic energy from the electric field of the collector space-charge region. The maximum additional kinetic energy that can be gained is Φ_{BC}, the total potential drop in the conduction band due to the applied base–collector voltage V_{CB}. High-velocity electrons in the central Γ valley (the region around the minimum energy in the electron conduction band) that have been accelerated to kinetic energies greater than the energy separation between the Γ minimum and the subsidiary conduction-band valleys



Excitation. This schematic diagram of a typical semiconductor band structure shows a valence heavy-hole band (1) with Fermi wavevector k_{F_1}, a light-hole band (2) with Fermi wavevector k_{F_2} and a conduction band (3). An electron with initial energy E and wavevector **k** in the conduction band can scatter inelastically by creating an excitation in the valence band of energy $\hbar\omega$ and wavevector **q**. The Fermi energy in the valence band is E_{F_h}. (Adapted from ref. 4.) **Figure 5**

around the X and L symmetry points of the crystal can scatter into these low-velocity states, for which $v \simeq 10^7$ cm/sec. Because of the high density of states associated with these subsidiary valleys, the probability of such Γ-to-X and Γ-to-L scattering is strong.

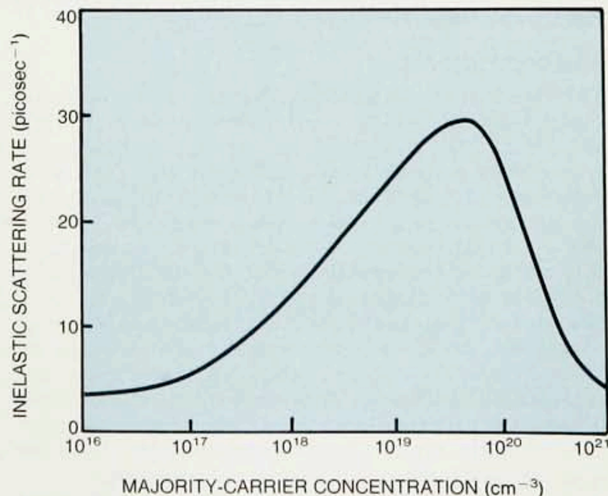
Clearly, it is useful to use semiconductors with large energy separations between the conduction-band minimum and the X and L valleys so that electrons can remain in the high-velocity Γ valley throughout the base and collector depletion region, even with a moderately large potential drop Φ_{BC} and with the collector junction reverse biased. The narrow-bandgap semiconductor $In_{0.53}Ga_{0.47}As$, which has a bandgap of about 0.7 eV, satisfies this condition ($E_{\Gamma L}$ is 0.55 eV, $E_{\Gamma X}$ is 1.15 eV), while GaAs, with its wider bandgap of about 1.5 eV, cannot ($E_{\Gamma L}$ is 0.3 eV, $E_{\Gamma X}$ is 0.5 eV). Because the collector transit time is an important delay in devices of the type shown schematically in figure 3, it should come as no surprise that heterostructure bipolar transistors fabricated from $In_{0.53}Ga_{0.47}As$ show significant high-frequency performance advantages over both GaAs and Si devices. Nevertheless, if large base–collector voltages are to be used ($\Phi_{BC} > 2.5$ eV), then neither GaAs nor $In_{0.53}Ga_{0.47}As$ has any performance advantage over Si.

High-frequency measurements

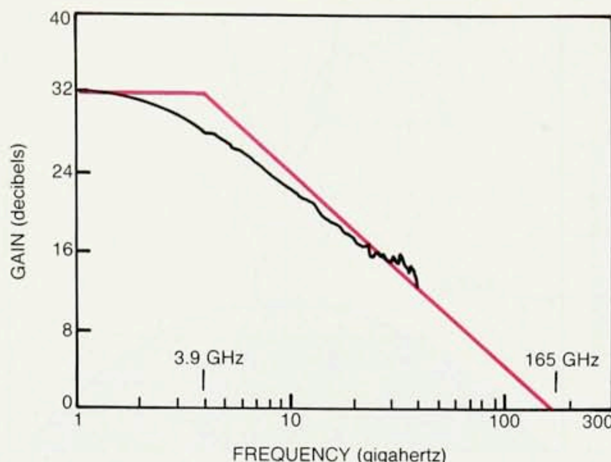
At low frequency the current gain of a high-quality heterostructure bipolar transistor is constant and is limited only by the back injection of p-type carriers from the base into the emitter. The current gain in conventional transistors decreases at high frequencies as a result of low average electron velocity and RC time constants. However, the transistors of interest to us here have RC time constants so low that the intrinsic transit-time delays due to high-velocity nonequilibrium electron transport is the limiting factor to the speed of operation.

More than a year ago heterostructure bipolar transistors were fabricated that approximately follow the design criteria outlined above[8]: nonequilibrium electron injection from a wide-bandgap emitter into a thin, heavily doped base, and a thin collector region of narrow-bandgap semiconductor with large intervalley separation. The devices have a wide-bandgap n-type InP emitter with an area of 3.5×3.5 square microns; the 500-Å-thick base is p-type $In_{0.53}Ga_{0.47}As$ doped to $1 \times 10^{20}/cm^3$; the narrow-bandgap n-type $In_{0.53}Ga_{0.47}As$ collector space-charge region is 3000 Å thick and doped to $3 \times 10^{16}/cm^3$, and the subcollector is heavily doped n-type material. The black curve in figure 7 represents typical measurements of the small-signal current gain $|h_{21}|$ at frequencies in the range 1–40 GHz. Following the custom among electrical engineers, we define the speed of the transistor by the cutoff frequency f_T at which the current gain falls to unity obtained by extrapolation using a −20-dB/decade decrease (the red line in figure 7). In our example the cutoff frequency f_T is 165 GHz.

This extrapolation procedure assumes that the transistor's small-signal microwave response may be interpreted in terms of a single, ensemble-average time constant. In principle, this assumption is incorrect, because the electron transit time through the collector space-charge region plays an important role in determining the intrinsic dynamic response of the device, and because the collector current flow involves at least two time constants: Electrons in the high-velocity central Γ valley have a very high-speed response, and those that have scattered into low-velocity subsidiary valleys respond much more slowly. By good fortune, however, our numerical simulations of device operation indicate that nonequilibrium central-valley transport dominates the small-signal microwave response. Thus the measurements are weighted toward the fastest electrons in the device, and in this situation,



Total inelastic scattering rate $1/\tau_{in}$ at 0 K as a function of the concentration of p-type carriers in $In_{0.53}Ga_{0.47}As$ for an electron injection energy E of 300 meV. **Figure 6**



Current gain as a function of frequency for an $InP/In_{0.53}Ga_{0.47}As$ heterostructure bipolar transistor. The black curve shows the measured room temperature small-signal common-emitter current gain at frequencies of 1–40 GHz. The transistor has an emitter area of 3.5×3.5 square microns, a collector current of 20 mA, and a collector–emitter bias voltage of 1.3 V. The red line points to a unity-gain cutoff frequency of 165 GHz—a measurement of the transistor speed. The frequency of the 3-dB current-gain roll-off is 3.9 GHz. (Adapted from ref. 8.) **Figure 7**

only one ensemble-average time constant is needed to model the transistor's high-speed small-signal operation.

The 165-GHz cutoff frequency measured at room temperature (300 K) corresponds to a total delay of less than 1 picosecond and to an average electron velocity through the active region—the base and collector—of 4×10^7 cm/sec. When the temperature is lowered to 80 K, the cutoff frequency increases to around 250 GHz because of reduced electron scattering and because of a decrease in emitter dynamic resistance, which is proportional to kT/I_E, where I_E is the emitter current. The reduction in electron scattering increases the average electron velocity through the transistor to more than 6×10^7 cm/sec.

Future problems

We have seen that the fastest bipolar transistors make use of high-velocity Γ-valley nonequilibrium electron transport in $In_{0.53}Ga_{0.47}As$. The intrinsic transit delay increases with increasing potential drop Φ_{BC} because of scattering into low-velocity subsidiary valleys in the collector space-charge region. Optimizing the collector bias avoids significant population of low-velocity subsidiary minima in the semiconductor. Calculations indicate that for a thin, highly doped base with an impurity concentration greater than $10^{20}/cm^3$ the base transit time is negligible and the collector transit time dominates the intrinsic transistor response. An important consequence is that ultrahigh-speed heterostructure bipolar transistors perform best with small signals and low collector voltages. In contrast, the typical digital electronic circuit uses the relatively slow large-signal response of transistors.

To the naive technologist, the prospect of a transistor ten times faster than silicon devices would warrant the development of a new technology. However, the lack of reliable, reproducible fabrication techniques limits this transistor, as well as any other bipolar III–V compound semiconductor device, to a modest level of circuit complexity. Some of the fabrication problems, such as low process temperatures and the absence of a robust native process oxide such as exists for silicon, are inherent obstacles to the development of a truly manufacturable product. For these and other reasons, we believe that the long-term future of purely electronic circuits based on III–V compound semiconductors is severely restricted. Silicon's dominance of digital electronics will continue, effectively unchallenged.

In the above discussion we have assumed that if new structures that use ballistic electron transport in semiconductors are to be developed, it might be helpful to understand the physics of device operation. Although such knowledge is not a necessary condition for the advancement of technology, it can speed its development and help investigators to make informed decisions about related work. In addition, extending the limits of transistor performance can expose deficiencies in our understanding of nonequilibrium electron transport. For example, in the description of electron motion through the device we adopted a semiclassical approach that, among other things, assumed collisions are local in space and time. Obviously this is not true for an electron accelerated in a large electric field, where the charge carrier can gain significant additional kinetic energy during a collision.

Further reduction in the thicknesses of the base and collector space-charge regions should open the way for substantial coherent electron transport between emitter and subcollector. In this situation semiclassical calculations, such as those discussed above, inadequately describe transistor operation, and an alternative, quantum mechanical description has to be used. As an example, quantum interference effects are important when large changes in electron velocity occur on the scale of the particle wavelength; Boris Gelfand and his coworkers at Bell Laboratories have pointed out that in this situation inelastic scattering, such as phonon emission, can influence elastic scattering, such as quantum mechanical reflection.[9] Clearly, much remains to be understood.

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