CHAPTER 7.3
MICROWAVE SEMICONDUCTOR DEVICES

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TYPES OF MICROWAVE SEMICONDUCTOR DEVICES

The number and variety of microwave semiconductor devices have greatly increased as new techniques, materials, and concepts have been applied. Silicon and compound semiconductor materials, such as gallium arsenide (GaAs) and indium phosphide (InP), are used for the fabrication of nearly all devices. The oldest structure is the tungsten-silicon *point-contact diode*, employing a metal-whisker contact, used for signal mixing and detection. The *Schottky barrier diode*, a rectifying metal-semiconductor junction, has supplanted the point contact because of its lower noise figure. These devices display a variable-resistance characteristic.

In contrast, the *variable-reactance (varactor) diode* makes use of the change in capacitance of a reverse-biased *pn* junction as a function of applied voltage. Physically, this capacitance change results from widening the depletion layer as the reverse-bias voltage is increased. By controlling the doping profile at the junction, the functional forms of this relation can be tailored to a specified application. Typical applications of varactor diodes are harmonic generation, parametric amplification, and electronic tuning.

pin diodes employ a wide intrinsic region which permits high-power-handling capability and offers an impedance at microwave frequencies controllable by a lower frequency (or dc) bias. They have proved useful for microwave switches, modulators, and protectors. In changing from reverse to forward bias the *pin* diode changes electrically from a small capacitance to a large conductance, approximating a short circuit.

For microwave power generation or amplification, a negative-resistance characteristic at microwave frequencies can be used. Beginning with the *tunnel diode* in the early 1960s and progressing to the higher-power *IMPATT diodes* and *Gunn diodes*, such negative-resistance devices experienced rapid development in the 1970s. The tunnel diode uses a heavily doped *pn* junction which is sufficiently abrupt for electrons to be able to tunnel through the potential barrier near zero applied voltage. Because this is a majority-carrier effect, the tunnel diode is very fast acting, permitting response in the millimeter-wave region. The very low power at which the tunnel diode saturates has limited its usefulness.

The *transferred-electron oscillator* (TEO), originally named for its discoverer J. B. Gunn, depends on a specific form of quantum-mechanical band structure for its negative resistance. This band structure is found in gallium arsenide, the semiconductor material generally associated with this class of device, and in a few other III-V compounds. *Gunn oscillators* have power output in the tens to hundreds of milliwatts at low dc operating voltage (9 to 28 V). They have a wide range of tunability and reasonably low AM and FM noise.

The *impact avalanche transit-time* (IMPATT) diode owes its negative resistance to the classical effects of phase shift introduced by the time lag between maximum field and maximum avalanche current multiplication and by the transit time through the device of this current. These effects can occur in all semiconductor *pn* junctions under sufficient reverse bias to initiate breakdown. While IMPATT diodes were originally developed as silicon devices (still the predominant type for millimeter waves), gallium arsenide IMPATTs are used because of their higher power (tens of watts). IMPATT diodes find applications in radar and millimeter wave transmitters.

Silicon bipolar transistors have penetrated the microwave region through the refinement of fabrication techniques based on the planar photolithography technology. By reducing the emitter width and base thickness to micrometer dimensions (and by paralleling stripes of structure to maintain power capability), transit times and charging times (resistance-capacitance product) can be kept low enough to provide useful devices with a maximum frequency of oscillation (f_{max}) of 22 GHz. Such transistors are also used in low-noise preamplifiers up to frequencies of about 4 GHz.

Heterojunction bipolar transistors (HBT) have been developed using GaAs and InP to take advantage of the superior electron transport in these materials. Heterojunction emitters using alloys of GaAs with ternary compound semiconductors such as aluminum gallium arsenide (AlGaAs) are used to improve the emitter injection efficiency for high current gain. Cutoff frequencies of 50 GHz have been achieved, about a factor of 2 better than silicon bipolar transistors.

Field-effect transistors (FETs) are microwave solid-state devices that use the higher mobility and saturated velocity of GaAs. The GaAs FET now dominates low-noise applications in the intermediate microwave region of the spectrum and has now taken over power-amplifier designs from the negative-resistance diodes discussed above. Noise figures less than 1 dB are obtained with low noise GaAs FETs at 10 GHz and below. Cutoff frequencies over 200 GHz have been achieved for new generation FETs, such as the *high electron mobility transistor* (HEMT). Power FETs have delivered power of 12 W at C-band for SATCOM amplifier applications.

Monolithic microwave integrated circuits (MMICs), using the monolithic integration of microwave transistors (both FET and bipolar) onto a single substrate, are now used in many high-frequency or high-speed applications. MMICs reduce the cost and size of RF and microwave components, in the same way as the use of silicon-integrated circuits have revolutionized computer and consumer electronics. GaAs and silicon MMICs provide circuit building blocks such as switches, amplifiers, oscillators, downconverters for such applications as cellular telephones, direct broadcast satellite TV receivers, and high-speed optical fiber communication systems.

Microwave Mixer and Detector Diodes

Mixing is defined as the conversion of a low-power-level signal from one frequency to another by combining it with a higher-power (local-oscillator) signal in a nonlinear device. In general, mixing produces a large number of sum and difference frequencies. Usually, the difference frequency between signal and local oscillator (the intermediate frequency) is of interest and is at a low-power level.

In *microwave detection,* solid-state devices are used as nonlinear elements to accomplish direct rectification of an applied RF signal. The sensitivity of a detector is usually much less than that of a superheterodyne receiver, but the detector circuit is simple and easy to adjust. The sensitivity has been improved considerably by the use of a wide-band low-noise microwave preamplifier preceding the detector.

Tunnel diodes, back diodes, point-contact diodes, and Schottky barrier diodes are majority-carrier devices that have nonlinear resistive characteristics and are useful for mixing and detecting. Noise figures lower than 6 dB are now possible at K_u band using Schottky barrier diodes. These improvements have resulted from better control of epitaxial material to achieve low series resistance and photolithographic techniques to achieve small-area Schottky diodes. Because of greater susecptibility to RF burnout, circuit complications, and fabrication difficulties, tunnel and back diodes have not found as wide acceptance as mixers and detectors at microwave frequencies. The point-contact (pressure contact between metal and semiconductor) and Schottky barrier diodes (formed by deposition of metal on semiconductor surface) are the primary mixer and detector microwave devices. However, back diodes are used in selected applications such as broadband low-level detectors and Doppler mixers.

Point-contact, Schottky barrier, and back diodes are used as mixers and detectors from UHF to millimeter frequencies. The construction and current-voltage characteristics of these diodes are shown in Fig. 7.3.1. The point is contact is fabricated by a metal whisker forming a rectifying junction in contact with the semiconductor. The Schottky is formed generally by an evaporated metal contact, and the back diode by an alloyed junction.

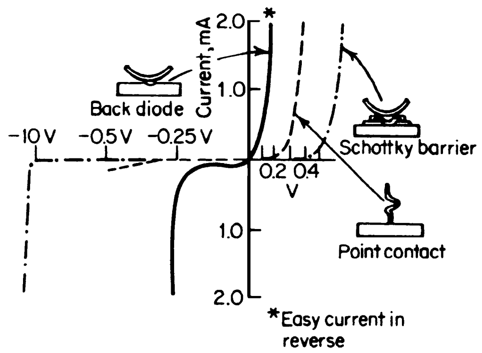

FIGURE 7.3.1 Current-voltage characteristics of back, point-contact, and Schottky barrier diodes. (*Proc. IEEE, August 1971.*)

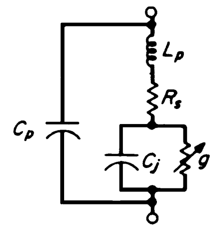

FIGURE 7.3.2 Equivalent circuit of microwave diode.

Point-Contact Diodes

The point-contact diode is the oldest structure. Until 1965 point-contact diodes were fabricated using moderately low resistivity material with the rectifying contact established by touching the semiconductor surface with a metal whisker (normally, tungsten for silicon and phosphorus bronze for germanium and GaAs).

Since that time the semiconductor epitaxial deposition has been applied to point-contact diodes (as well as to Schottky diodes) to maximize the frequency cutoff (minimize the R_sC_j product). This is a significant consideration since conversion loss is directly proportional to the product of diode series resistance R_s and junction capacitance C_j, as shown in Fig. 7.3.2.

Such devices are generally used only in the millimeter-wavelength range because of inherent reproducibility problems and because they have poorer noise figures than Schottky diodes. Nevertheless they are more resistant to RF burnout than the Schottky devices.

Schottky Barrier Diodes

The Schottky barrier diode is a rectifying metal-semiconductor junction formed by plating, evaporating, or sputtering a variety of metals on *n*- or *p*-type semiconductor materials. Schottky diodes are fabricated from n-on-n^+ epitaxial material (*n* layer 0.5 to 1.0 μm thick), where the *n* layers are optimized in thickness and carrier concentration for minimum conversion loss and maximum RF burnout or power-handling capability. Because of their higher cutoff frequency, GaAs devices are preferred in applications above X-band frequencies. This results from the higher mobility of electrons in GaAs than in silicon. Although in practice this advantage is not as significant as predicted, a conversion-loss improvement of 0.5 dB at K_u band is readily obtainable with GaAs, compared with silicon.

Schottky diodes are fabricated by a planar technique. A SiO_2 layer (1 μm thick) is thermally grown or deposited on the semiconductor wafer, and windows are etched in the SiO_2 by photolithography techniques. Schottky junctions are formed by evaporation, sputtering, or plating techniques. Metal on the oxide is removed by a second photo step. Junction diameters as small as 5 μm are made by this technique. Schottky diodes are also fabricated with attached gold leads, using the beam lead process. After completion of the Schottky contact metallization step, thick gold contact leads are plated on the junction side of the wafer. The backside of the wafer is patterned and etched to form isolated diodes and to expose the gold beams on the frontside of the wafer. Figure 7.3.3*a* shows a silicon diode intended for operation at X band, and Fig. 7.3.3*b* shows a beam lead diode for millimeter waves.

Mixer-Diode Parameters

Figure 7.3.4 gives the noise figure for a variety of mixer diodes as a function of local oscillator power at 16 GHz. Below this frequency, silicon Schottky diodes exhibiting a minimum noise figure of 5.5 dB are generally used, while GaAs is preferred at higher frequencies.

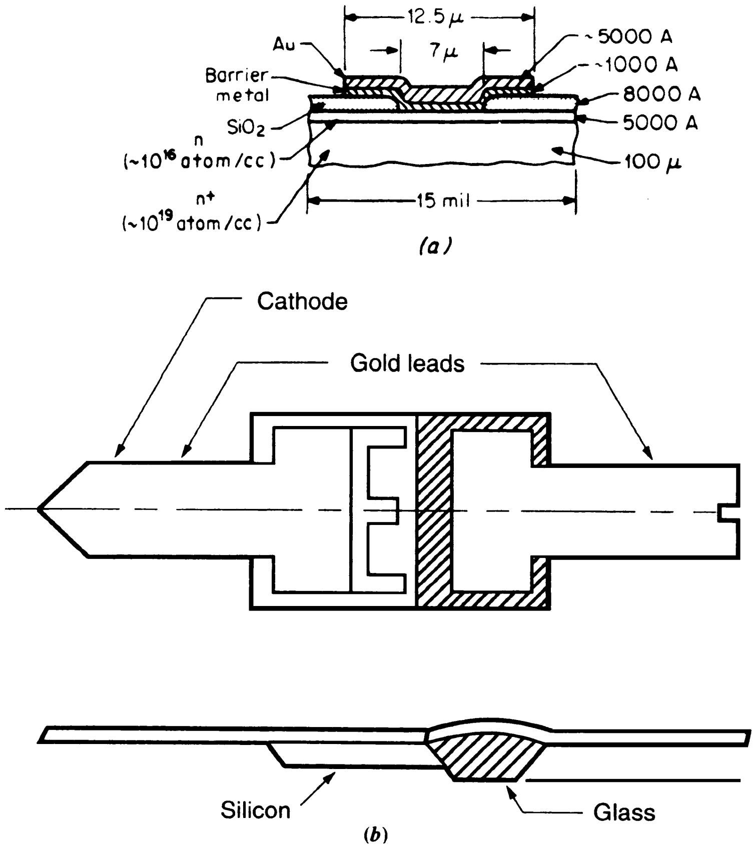

FIGURE 7.3.3 Microwave diodes: (*a*) silicon diode for operation at X band; (*b*) beam lead diode for stripline and microstrip circuits.

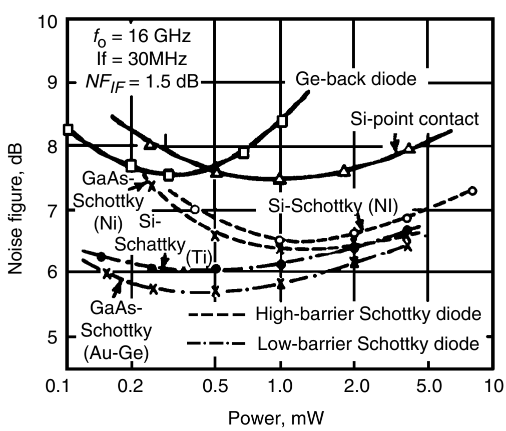

FIGURE 7.3.4 Noise figure vs. local oscillator power for point-contact diodes and *n*-type Schottky barrier diodes.

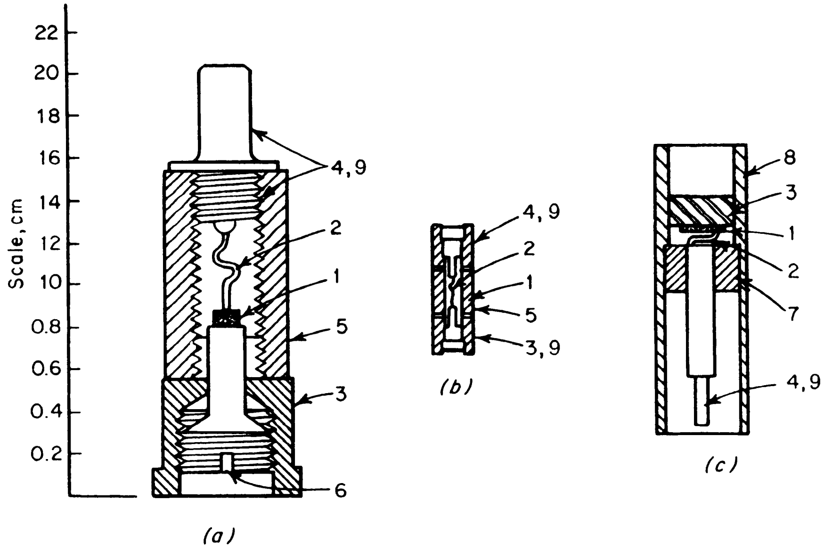

FIGURE 7.3.5 Mixer and detector diode packages: (1) semiconductor; (2) whisker; (3) wafer contact; (4) external whisker contact; (5) ceramic case; (6) adjustment screw; (7) insulating spacer; (8) outer conductor; (9) connection to i.f. amplifier or detector. *(After H. A. Watson, "Microwave Semiconductor Devices and Their Circuit Applications," McGraw-Hill, 1969)*

The *tangential signal sensitivity* (TSS) is the most widely used criterion for detector performance. It indicates the ability of the detector to detect a signal against a noise background and also includes the noise properties of the diode and video amplifier. This quantity varies with the square root of the amplifier bandwidth, since square-law response is obtained at low signal levels. As a rough basis of comparison, the TSS rating corresponds to a signal-to-noise of about 2.5. Biased silicon Schottky diodes have a typial TSS of –55 dBm at 10 GHz. For RF monitor applications, voltage sensitivity in microvolts per microwatt is important and a typical value of 7 mV/μW is achieved. Low barrier (or zero bias) detectors provide a higher sensitivity at higher video resistance.

Typical mixer- and detector-diode packages are shown in Fig. 7.3.5. They are designed to be compatible with a particular type of microwave circuitry, waveguide, coaxial, or strip line. The packages shown in Figs. 7.3.5*a* and *b* are generally used up to about 12 GHz. The coaxial package in Fig. 7.3.5*c* permits operation up to about 30 GHz. Stripline or microstrip mixer circuits generally use beam lead diodes, owing the planar lead configuration of the beam lead design. Multiple diodes are fabricated on the same chip, as monolithic pairs or quads for use in balanced or doubly balanced mixers. Balanced mixers provide noise and local oscillator cancellation at the IF port, but at the expense of higher local oscillator power.

Varactor Diodes

The active element of a varactor diode consists of a semiconductor wafer containing a *pn* junction of a well-defined geometry, usually formed by diffusion. Varactor diodes are normally operated under reverse bias, where the junction resistance (ordinarily 10 MΩ or more) is negligible in comparison with the microwave capacitive reactance of the junction. The variable capacitance C_j (Fig. 7.3.6) of the varactor diode as a function of applied voltage is used to tune microwave circuits such as voltage-controlled oscillators (VCOs). *Hyperabrupt junction* doping profiles provide a more rapid change in capacitance (and frequency tuning) as a function of voltage than abrupt junction diodes.

For forward bias the diode current increases exponentially with the applied voltage, and for reverse bias a small saturation current I_s flows. When the reverse bias is increased to the avalanche breakdown voltage V_B, the diode reverse current increases very rapidly, since it is limited only by the small diode resistance and any external resistance present in the circuit.

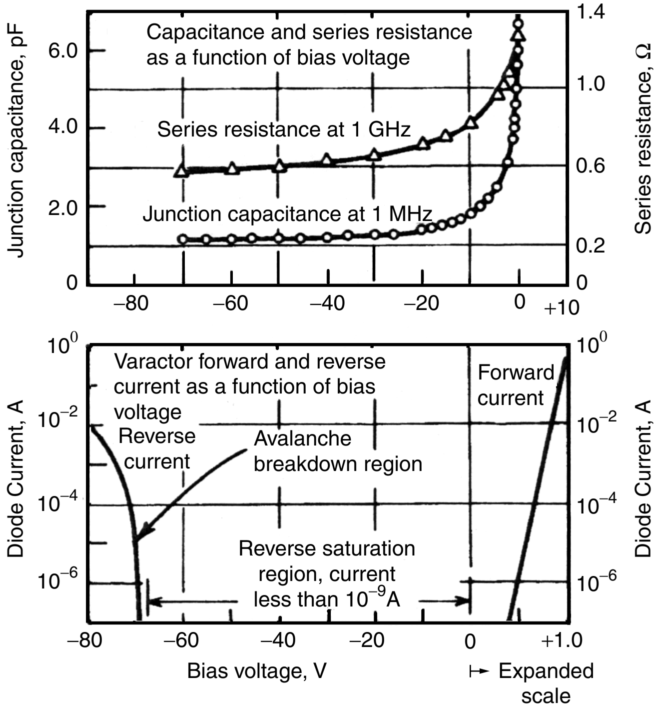

FIGURE 7.3.6 Varactor junction capacitance, series resistance, forward current, and reverse current as functions of bias voltage. *(After H. A. Watson, "Microwave Semiconductor Devices and Their Circuit Applications," McGraw-Hill, 1969)*

Figure 7.3.7 shows typical dc current-voltage characteristics, microwave series resistance, and 1-MHz capacitance-voltage characteristics.

Varactor Packages. Typical varactor diodes are mounted in hollow dielectric (usually alumina) cylinders with Kovar or copper end caps, as shown in Fig. 7.3.7. A flexible connection is made to the diode mesa from one end cap by means of a thin gold strap. The equivalent circuit shown represents the coupling between the diode junction region and the package surface.

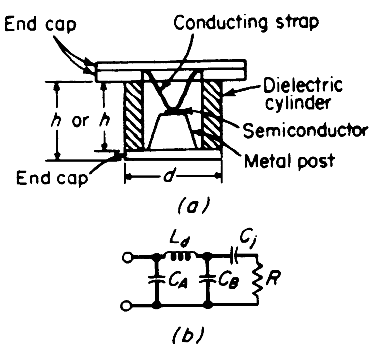

FIGURE 7.3.7 Low inductance diode construction and equivalent circuit. (*Microwave J., November 1970*).

Charge-storage effects. In some applications the injected charge-storage capacitance is more important than the capacitance variation associated with the varying width of the depletion region. Charge-storage capacitance is produced by the injection of minority carriers during the forward-biased excursion of the varactor pump voltage and the withdrawal of this charge during the reverse-biased portion of the cycle. The resultant waveform is shown in Fig. 7.3.8. Efforts to maximize charge-storage effects in microwave diodes have led to a class of devices known as *snap-back,* or *step-recovery, diodes.* They feature steep doping profiles and narrow junctions, to give fast recovery of injected charge, typically in a transition period of a few tenths of a nanosecond, yielding a high-harmonic content. However, this design results in lower breakdown voltage, reducing the power capability of the

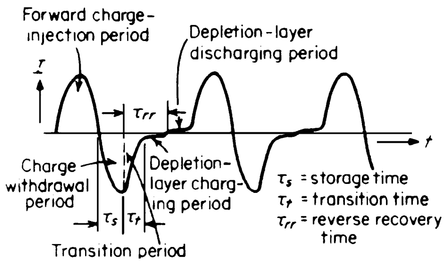

FIGURE 7.3.8 Current waveform of sinusoidally switched step-recovery diode. (*After H. A. Watson, "Microwave Semiconductor Devices and Their Circuit Applications," McGraw-Hill, 1969*)

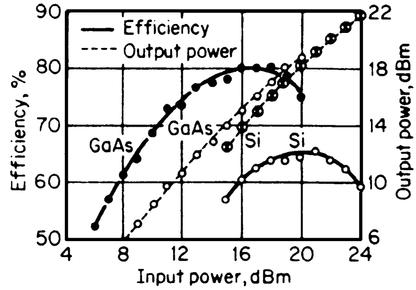

FIGURE 7.3.9 Conversion efficiency and output power of varactors used as frequency triplers, with bias adjusted to maximum output as each point. (*After H. A. Watson, "Microwave Semiconductor Devices and Their Circuit Applications," McGraw-Hill, 1969*)

diode. Frequency multipliers use these diodes when high-order multiplication (above eight) and circuit simplicity are desired, at the expense of power output.

Varactor Frequency Multipliers

Figure 7.3.9 gives the characteristics of diffused epitaxial GaAs and Si varactor diodes employed in a conventional tripler (4 to 12 GHz) frequency multiplier. Because of its higher cutoff frequency, GaAs gives higher efficiency but lower maximum output power than Si. Frequency triplers with output at 220 GHz have been fabricated for submillimeter wave sources.

pin Diodes

pin diodes consist of heavily doped *p* and *n* regions separated by a layer of high-resistivity intrinsic material. Typical construction of such a diode is shown in Fig. 7.3.10. Under zero and reverse bias this type of diode has a very high impedance, whereas at moderate forward current it has a very low impedance. This permits its use as a switch in microwave transmission lines. Generally, the diode is placed in shunt across a strip line, allowing unimpeded transmission when reverse-biased but short-circuiting the line to produce almost total reflection when forward-biased by as little as 1 V. In attenuator applications the diode behaves like a current-controlled resistance in parallel with the capacitance of the intrinsic region. For stripline or microstrip circuits, beam-leaded *pin* diodes similar to those of Fig. 7.3.3*b* are used, whereas the low-inductance package of Fig. 7.3.7 is used for high-power applications.

The wide intrinsic layer permits high microwave peak power to be controlled since the breakdown voltage is of the order of 1 kV. Very little power is dissipated by the diode itself because reflection switching is employed. *pin* diodes can be used as limiters, replacing TR tubes for peak powers smaller than 100 kW. At higher peak power, these diodes are useful, following the TR box to eliminate any spike leakage, although if fast response is required (less than 1 μs) a varactor diode is used.

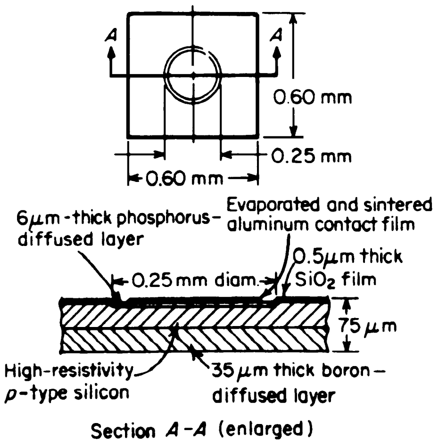

FIGURE 7.3.10 Typical planar *pin* microwave wafer.

Electrically controllable, rapid-acting microwave phase shifters are finding increasing use in phased-array systems. *pin* diodes are employed to switch lengths of transmission line, providing digital increments of phase in individual transmission paths, each capable of carrying many kilowatts of peak power.

Transferred-Electron (Gunn) Devices

The negative resistance that leads to oscillation for this class of device is a consequence of the band structure of certain semiconductors. An upper conduction band must exist in which carriers have lower mobility than in the initially occupied lower band. The transfer of carriers, generally electrons, from the lower to the upper conduction band takes place as a result of lattice collisions as the electric field strength across the material is increased.

The transfer leads to a reduced current as the voltage increases and therefore represents a negative resistance on the *v-i* curve. The velocity-electric field characteristics of two materials that exhibit this behavior are shown in Fig. 7.3.11. By comparison, silicon has a monotonic characteristic which lies well below the curve for GaAs.

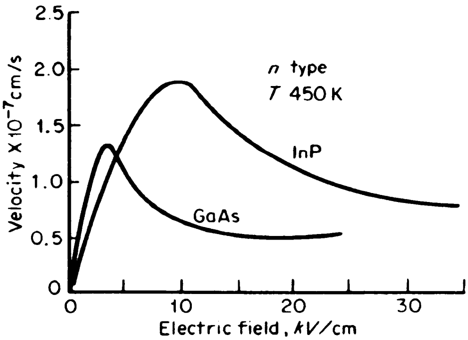

FIGURE 7.3.11 Velocity vs. electric field of indium phosphide and gallium arsenide.

Fabrication of Gunn Devices. The fabrication of these devices requires stringent control over the material. Good electrical performance results from extremely pure and uniform material with a minimum of deep donor levels and traps and the use of very-low-loss contacts. Modern devices use an *n*-type epitaxial layer of GaAs or InP grown from the vapor phase on n^+ bulk material. Typical carrier concentrations range from 10^{14} to 10^{16} cm^{-3}, while device lengths range from a few to several hundred micrometers.

Noise. One of the more important operating characteristics of the Gunn type of oscillator is its low-noise performance compared with other types of microwave sources at frequencies above 18 GHz. Phase noise for an InP Gunn diode oscillator is typically −87 dBc/Hz measured at 100 kHz offset from the oscillator frequency of 38 GHz.

Electronic Tuning. Electronically tuned Gunn oscillators are available employing YIG spheres, varactor diodes, and *pin* diodes as the tuning element, in addition to mechanically tuned devices. Typical ranges covered are 8 to 12 and 12 to 18 GHz at the rather slow YIG magnetic-tuning speed of 100 Hz and of the order of 10 percent bandwidth at the much faster varactor rate of up to 10 MHz for oscillators up to 40 GHz.

Applications. While Gunn diodes have been used in reflection amplifiers with a ferrite circulator to separate input from output, the advent of the GaAs FET, with its superior noise and power-amplification characteristics, has relegated the transferred-electron devices to oscillator (TEO) use.

The continuing development of indium phosphide (InP) Gunn devices has led to oscillators and reflection amplifiers at wavelengths in the 3- to 5-mm range, a region GaAs devices (TE or FET) cannot reach at present. The performance advantage is a consequence of the superior higher efficiency of InP devices. For example, InP Gunn diode oscillators have achieved a DC-to-RF conversion efficiency of nearly 3 percent at 140 GHz at an output power of 65 mW. Figure 7.3.12 displays the power and efficiency of cw InP Gunn diodes from 35 to 140 GHz.

Microwave Avalanche (IMPATT) Diodes

The power obtainable from IMPATT devices is greater than that available from the Gunn diodes described above but at the expense of higher noise and higher operating voltage. Two fundamental physical processes are pertinent to the operation of avalanche diodes: the drift velocity at which carriers travel under a reverse-biased electric field and the avalanche multiplication which occurs at sufficiently high fields.

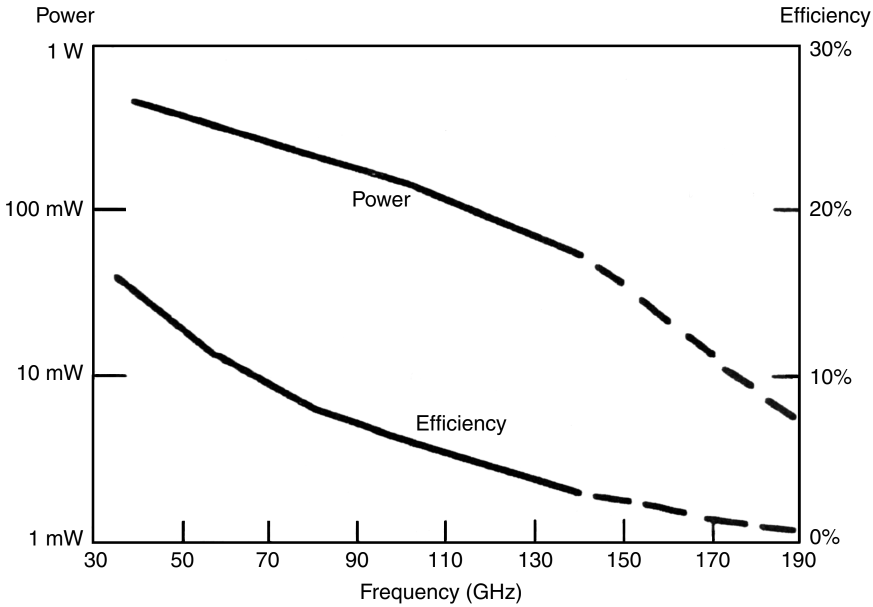

FIGURE 7.3.12 Power and efficiency of InP Gunn diodes. (*Crowley, Litton Solid State*)

Theory of Operation. An understanding of the dynamic operating characteristics of IMPATT diodes can be best obtained by considering the operation of the structure shown in Fig. 7.3.13. The IMPATT diode consists of two regions: a narrow avalanche region (*p* region), in which carrier multiplication by impact ionization occurs, and a drift region (*n* region), in which the carriers drift at saturated or field-independent velocities and where no impact ionization occurs.

The negative resistance or conductance of an IMPATT diode is attributed to phase shift between the current through the diode and the voltage across it. This phase shift consists of two components. There is a phase delay of the current caused by the avalanche multiplication process and by the finite transit time of the holes drifting through the drift region. If the diode is to operate as a stable oscillator, the negative conductance of the diode must decrease with increasing RF voltage. The RF voltage across the diode will grow until the admittance of the diode is balanced by the admittance of the microwave circuit.

At a sufficiently low frequency the phase delay of the transit time plus the phase lag of the avalanche process are not sufficient to have the fundamental component of the external current lag the RF voltage by more than 90°. Therefore, below a certain cutoff frequency, the conductance of the diode becomes positive.

At present the semiconductor materials used in commercial IMPATTs are silicon and gallium arsenide. The latter is operated in this case at much higher electric fields than corresponds to the region of negative differential mobility utilized in the Gunn effect. The basic structure of a typical *pn* junction silicon IMPATT is shown in Fig. 7.3.13. In operation the device is reverse-biased past the point of avalanche breakdown, so that a direct current of 50 to 500 mA flows through the diode.

Significant improvement in performance is obtained, however, by modifying the doping profile so that the

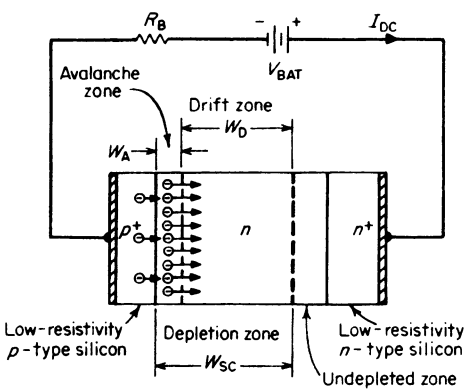

FIGURE 7.3.13 *pn* junction of IMPATT diode under reverse bias. (*After Cowley, WESCON, 1971*)

high-field avalanche region is narrowly confined and the electric field is optimized separately for the drift region. Such profiles, called high-low, low-high-low, and double-drift, yield efficiencies of 20 to 35 percent compared to 6 to 10 percent and 10 to 15 percent obtained from flat-profile Si and GaAs, respectively.

GaAs IMPATTs are preferred for frequencies up to 30 GHz because of their performance advantages, especially for pulsed radar transmitters at X band. Efficiencies of 20 percent are obtained at output powers of 15 W for low duty cycle RF waveforms. Multiple diodes are combined in an RF cavity to obtain 100 W. Si IMPATTs are used in the millimeter wave range and currently give the highest power available from a solid-state device in this frequency region.

Fabrication. The IMPATT structure is fabricated by first growing a thin epitaxial layer of *n*-type silicon or GaAs on a heavily doped *n*-type (n^+) substrate and then adding a *p* layer by growing an epitaxial layer or by ion implantation. Finally, a thin platinum contact layer is formed by diffusion giving a p^+pnp^+ double-drift structure. For 94-GHz operation, the epitaxial-layer thickness is of the order of 0.5 μm, and the diameter of the diode is of the order of 50 μm.

Cooling. A difficult technological problem in IMPATT diode packaging is efficient heat removal from the active portion of the device. These diodes operate at high dc power densities, typically 10 to 100 kW/cm^2, and since only a fraction (6 to 12 percent) is converted to RF power, the remainder must be removed as heat. Inverted mesa thermocompression bonding to a copper heat sink has been employed for this purpose. A better approach electroplates the heat sink at the wafer stage before individual diodes have been fabricated. Diamond has also been employed as a heat sink in experimental devices using inverted chips.

Microwave Bipolar Transistors

To achieve operation at microwave frequencies, individual transistor dimensions must be reduced to the micrometer range. To maintain current and power capability, various forms of internal paralleling on the chip are employed. These geometries fall into three general types, as shown in Fig. 7.3.14, interdigitated fingers forming emitter and base, overlay groupings of emitter and base stripes, and a mesh or matrix of emitter and base spots. All microwave transistors are now planar in form, and almost all are of the silicon *npn* type.

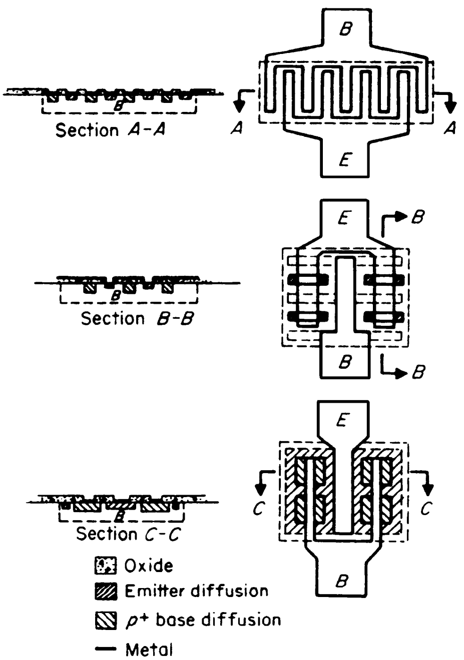

FIGURE 7.3.14 Typical geometrics of bipolar microwave transistors.

Construction and Fabrication. Silicon microwave transistors are built up on an *n*-type epitaxial layer of the order of 1 Ω·cm resistivity (deposited on lower-resistivity silicon) to keep the collector depletion layer narrow. Diffusion of *p*-type dopant (typically boron) is used for the base. More recently ion implantation has replaced diffusion as the means of achieving base widths of less than 0.1 nm.

Following base formation, the emitter is then defined through photomasks, and the appropriate dopant (phosphorus or preferably arsenic) diffused in. Metal contacts are then evaporated or sputtered to interconnect the elements of the device.

Figure 7.3.15 illustrates the steps in the fabrication process. Reduction of strip width to increase frequency response has been made possible by improved lithography and etching, leading to state-of-the-art line definition of 1 nm.

Power Capability. Most power microwave transistors include some form of integral emitter resistors to aid in equalizing the current over the distributed emitter structure.

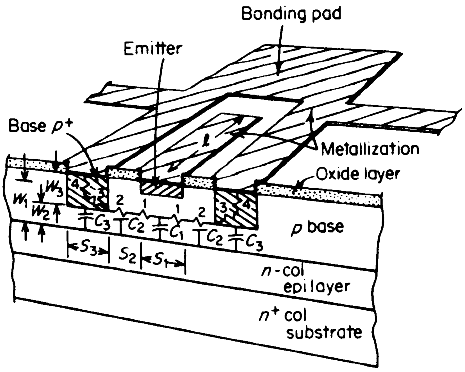

FIGURE 7.3.15 Cross section of planar transistor, showing (1)–(3) r'_b and (4) contact resistance R_C. (*Proc. IEEE, August 1971*)

The *overlay transistor* has an integral diffused resistor as part of each emitter stripe, while *thin-film resistors* are deposited as part of the contacts on interdigitated devices. Guard rings are employed to raise the voltage breakdown limit of the collector to about half that of bulk silicon.

A figure of merit can be defined for the transistor in terms of the base resistance r'_b, the collector capacitance C, and the emitter-to-collector signal delay time τ_{ec}:

$$(\text{Power gain})^{1/2}(\text{bandwidth}) \approx 1/4\pi(r'_b C\tau_{ec})^{1/2}$$

τ_{ec} is composed of the transit time of carriers across the base and collector depletion layer plus the charging time of the emitter-base junction capacitance and the collector capacitance. The maximum frequency of oscillation is obtained by setting the gain equal to unity in this expression.

Silicon bipolar transistors provide the highest pulsed output power of any solid-state microwave or RF device, up to 500 W at collector voltages of 50 VDC. In linear amplifier operation, bipolar transistors are used in personal communications network (PCN) and cellular base stations with output power capability of 30 W at 1.9 GHz. Figure 7.3.16 illustrates the output power capability of bipolar transistors from 900 MHz to 20 GHz. The projected maximum frequency of oscillation for silicon bipolar transistors is 22 GHz.

Noise. The principal sources of noise in a microwave transistor are shot noise associated with the emitter and collector current and thermal noise in the base resistance. It is an increase in the latter and reduction in current gain which are responsible for the deterioration of noise figure with frequency. The current state of the art in the bipolar-transistor noise figure is about 2 dB at 4 GHz, increasing to 5 dB at 6 GHz.

Because of the high current gain at low currents, silicon bipolar transistors are used as amplifiers and oscillators in many portable applications up to 2.5 GHz. The transistors are also widely used in VCOs up to 20 GHz, because of their low 1/*f* noise.

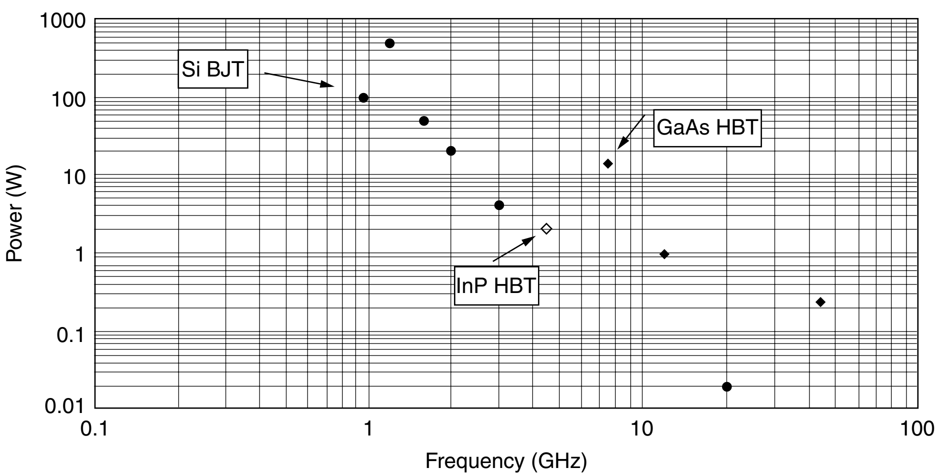

FIGURE 7.3.16 Performance of microwave power transistors as of 1979 and projected improvement. (*Trans. IEEE, May 1979, Vol. MTT 27, No. 5*)

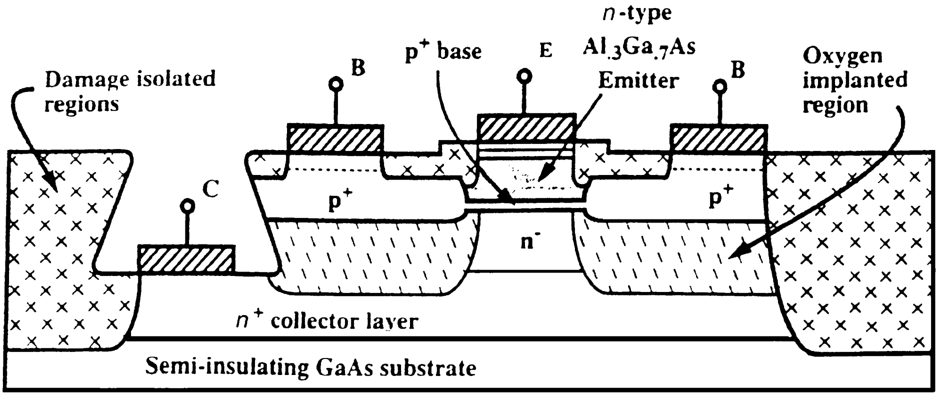

FIGURE 7.3.17 Cross section of GaAs HBT, showing AlGaAs emitter and low collector.

Heterojunction Bipolar Transistors

Heterojunction bipolar transistors (HBTs) fabricated on GaAs take advantage of the high electron mobility for electron transport across the base of the device. A cross section of an HBT is shown in Fig. 7.3.17. The emitter of highly doped, *n*-type AlGaAs forms a heterojunction with the highly doped GaAs *p*-type base (called the heterojunction due to different crystalline composition), resulting in favorable electron injection into the base. DC current gains are typically 20 to 200, with cutoff frequencies above 50 GHz. The devices are fabricated with all-epitaxial growth by means of molecular beam epitaxy (MBE) or metallo-organic chemical vapor deposition (MOCVD). HBT base and collector layers are similar in thickness to those for silicon bipolar transistors, but the emitter width can be wider (1 to 3 μm) because of the faster base transit time and lower capacitance per unit area. To achieve high gain, oxygen implantation is used to reduce the base-collector capacitance under the base contact.

The unity current gain figure-of-merit, f_T, and the maximum frequency of oscillation for GaAs HBTs range from 30 to 60 GHz, exceeding the same silicon bipolar transistor figures of merit by over two times. The power capability of the GaAs HBT from 7.5 to 44 GHz is compared to the silicon bipolar transistor in Fig. 7.3.16. Output power of over 10 W has been achieved at 7.5 GHz with 40 percent power-added efficiency.

HBT devices have also been fabricated on InP substrates, using an InAlAs emitter and InGaAs base, with f_{max} over 100 GHz. Silicon-based HBTs, using a silicon-germanium alloy base layer, have also been fabricated, with figures-of-merit over twice those of silicon homojunction devices. SiGe HBTs offer the promise of high performance with the lower cost of silicon processing, compared to GaAs and InP devices.

Field-Effect Transistors

The schematic in Fig. 7.3.18 illustrates the field effect transistor principle of operation. The flow of charge carriers from source to drain is controlled by the potential applied to the gate electrode. This flow takes place in a thin layer of *n*-type GaAs, called the channel. The gate is generally a Schottky barrier formed by deposition of an appropriate metal, leading to the acronym MESFET. The channel of the MESFET is fabricated by either epitaxy (MBE, MOCVD, VPE) or ion-implantation. The latter is more commonly used for general-purpose MESFETs, while epitaxy is used for low-noise devices.

The electron current from source to drain is determined by the depth of the depletion layer formed under the gate by the negative potential applied to it. The frequency response of this type of amplifier goes up as the gate length is reduced, while its power output increases linearly with gate width. Typical gate lengths range from 1/4 to 1 μm, while gate widths vary from a fraction of a millimeter for low-noise FETs to tens of millimeters for power devices. About 0.5 W of microwave power per millimeter is a widely used figure of merit.

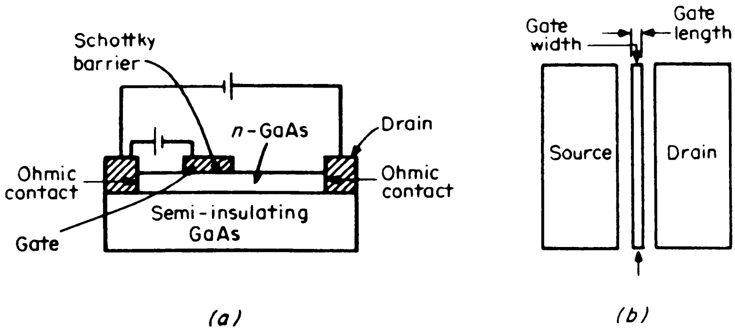

FIGURE 7.3.18 (*a*) Schematic and (*b*) dimensions of a single-gate Schottky barrier GaAs field-effect transistor. (*Microwave J., November 1978*)

Noise of the MESFET. The GaAs MESFET achieves its low-noise figure from the thermal noise characteristic of the majority carrier (electron) flow in the channel. The typical noise figure of a 0.3-μm gate length MESFET is shown in Fig. 7.3.19. The MESFET is 1.4 dB lower in noise figure at 4 GHz (0.6 vs. 2 dB) with over 14 dB gain, as compared to the silicon bipolar, and is widely used in low-noise amplifiers from 1 to 20 GHz. However, the heterojunction FET is now displacing the MESFET as a low-noise amplifier because of even lower noise figure.

The heterojunction FET has evolved from the earlier high electron mobility transistor (HEMT) to an improved (for lower noise and higher gain) epitaxial layer design called pseudomorphie HEMT (PHEMT). The noise figure of a 0.3-μm gate length PHEMT is also shown in Fig. 7.3.19; note that the noise figure is reduced by 0.7 dB over the MESFET noise figure at 12 GHz. Further improvements in gain have been achieved with the use of 0.1 μm gates and InP epitaxial structures, where f_{max} has exceeded 250 GHz.

Power of the MESFET. A parallel interconnection of MESFET cells is used to increase the power handling capability in accordance with the power figure of merit of 0.5 W/mm of gate width. The number of gates is chosen on the basis of the cell gate length and width; typical cell dimensions are gate length of 0.5 μm by 125 μm width by 12 gates per cell. To achieve 25 W at 5 GHz, four chips of 12 cells each are connected to

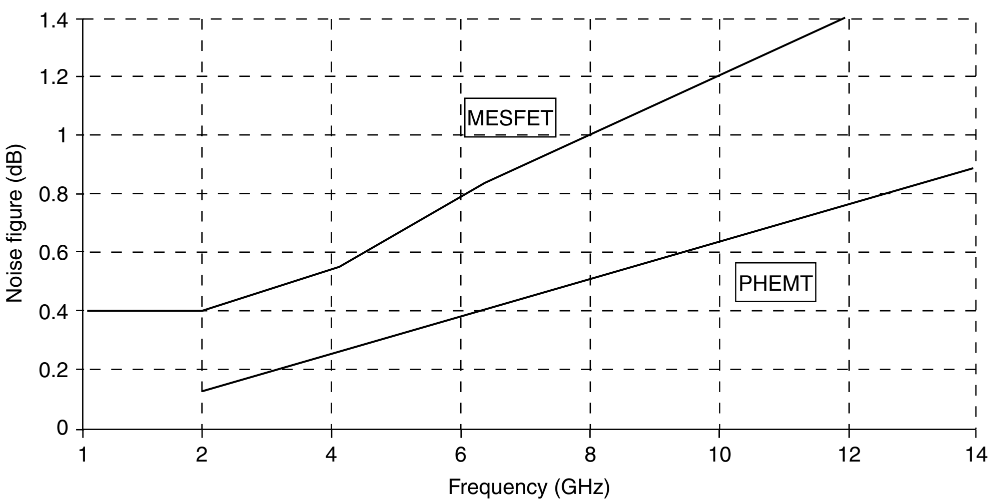

FIGURE 7.3.19 Noise figure of MESFET and PHEMT devices.

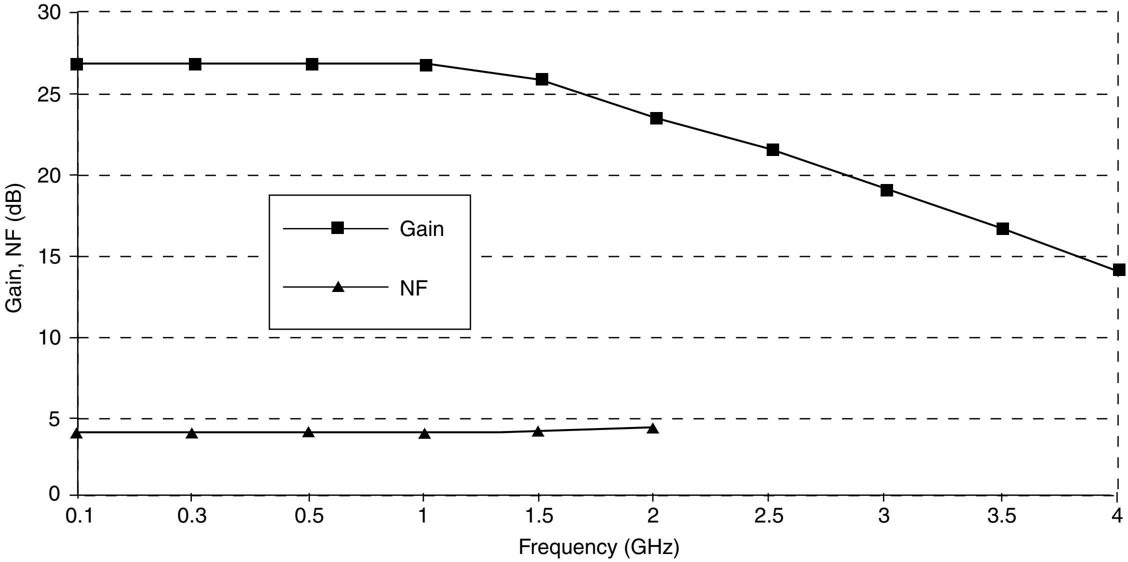

FIGURE 7.3.20 Gain and noise performance of silicon bipolar RFIC.

yield a total width of 72 mm. The chips are interconnected in a single package, using matching networks internal to the transistor package.

Silicon Bipolar RF and Microwave Integrated Circuits

Integrated circuits using high f_T silicon bipolar transistors are available with complexity ranging from simple single-stage amplifiers to functional blocks, such as vector modulators and downconverters. Resistors and capacitors are integrated onto the same semiconductor chip with a number of transistors and diodes to form microwave integrated circuits for applications from 100 MHz to 3 GHz. The RF gain and noise figure of a typical silicon RFIC, using feedback around a Darlington transistor to obtain a gain greater than 20 dB up to 3 GHz, are shown in Fig. 7.3.20.

More complex circuits have been developed that provide nearly the entire front end of a global positioning satellite receiver, comprising a dual downconversion design. Silicon bipolar integrated circuits have also been designed for new generation cellular telephone transmitters and receivers. Complementary MOS transistors have been combined with bipolar transistors on the same chip (using the *BiCMOS* process) to implement advanced functions for low-power portable telephones.

GaAs Monolithic Microwave Integrated Circuits

Monolithic microwave integrated circuits (MMICs) using GaAs MESFETs as the active elements and monolithically integrated with matching circuits have replaced the discrete circuit implementation in many RF and microwave designs. GaAs MMICs are available for applications from 500 MHz to 40 GHz, with developmental devices having gain to 100 GHz.

The fabrication of GaAs MMICs is facilitated by the use of a semi-insulating substrate as used for MESFETs, permitting the placement of microstrip matching elements and other passive components on the same semiconductor chip with minimum parasitic capacitance and loss. The functional diagram of an amplifier/switch MMIC for 2.4 to 2.5 GHz transmit/receive function is shown in Fig. 7.3.21. The receive path contains

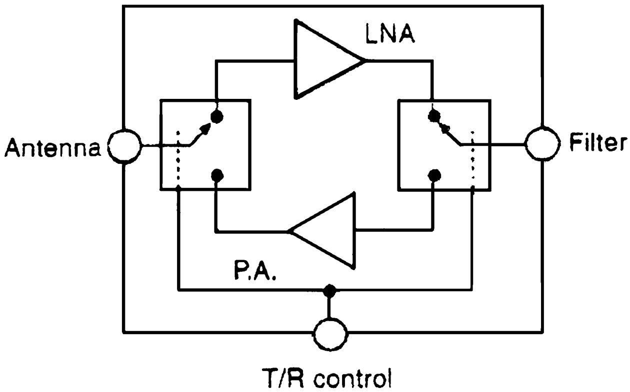

FIGURE 7.3.21 Functional diagram for 2.4 GHz GaAs transceiver. (TriQuint Semiconductor)

a high gain, low-noise amplifier, internally matched to 50 Ω at both ports. The transmit path contains an internally matched, class-A, medium power amplifier. The circuit also contains fully integrated T/R switches at input and output. The use of GaAs MESFETs as amplifiers provide both low-noise figure (3.5 dB) as well as good linearity for the transmitter in applications such as spread spectrum transceivers.

For millimeter wave amplifiers MESFETs can be replaced by PHEMTs, which have higher gain. A broadband power amplifier MMIC has been fabricated with a nominal gain of 13 dB and output power of +21 dBm from 20 to 50 GHz.

Other GaAs MMICs have been developed with greater complexity that provide an entire downconverter for satellite TV receivers at 12 GHz. Low-power radar transceiver MMICs at 94 GHz have been demonstrated in the laboratory that may provide collision warning sensors for automobiles by the year 2000.

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