12

Semiconductor Microwave Devices and Circuits

No segment of the microwave field has had more research devoted to it, over the past three decades, than the field of solid-state devices and circuits. This has resulted in a tremendous proliferation of, and improvements in, semiconductor devices for microwave amplification, oscillation, switching, limiting, frequency multiplication and other functions. For the systems designer, the result of these continuing improvements has been greater flexibility, improved performance, generally greater reliability, reduced sizes and power requirements, and importantly the ability to produce some systems that would not otherwise have been possible.

It would be entirely feasible to write a large book on each of the major sections of this chapter. In this chapter we will explain the basic principles of each type of device, to discuss its practical aspects and applications, to describe and show its appearance, and to indicate its state-of-the-art performance figures. Different devices that may be used for similar purposes will be compared from a practical point of view. A number of explanations will be deliberately simplified because of the complex nature of the material.

The chapter begins with an explanation of certain passive microwave circuits, notably *microstrip, stripline* and *surface acoustic wave (SAW)* components. They are not semiconductor devices themselves, but since they are often used in conjunction with solid-state microwave devices, this is a convenient place to review them.

We then continue with a presentation of microwave transistors, both bipolar and field-effect. As with microwave triodes in the preceding chapter, it will be assumed that students already understand how transistors work. We will then discuss their high-frequency limitations and what makes microwave transistors different in construction and behavior from lower-frequency ones. The section concludes with an introduction to microwave integrated circuits.

The next section is devoted to varactor diodes. These are diodes whose capacitance is linearly variable with the change in applied bias. This property makes the diodes ideal for electronic tuning of oscillators and for low-loss frequency multiplication. Another important application of varactors is in *parametric amplifiers*, which form the next major portion of the chapter. Extremely low-noise amplification of (microwave) signals can be obtained by a suitable variation of a reactive parameter of an RLC circuit. Varactor diodes fit the bill, since their capacitance parameter is easily variable.

Tunnel diodes and their applications are the next topic studied. They are diodes which, under certain circumstances, exhibit a negative resistance. It will be shown that this results in their use as amplifiers and oscillators. Tunnel diodes will be used as an example of how amplification is possible with a device that has negative resistance.

The *Gunn effect* and *Gunn diodes*, so-called after their inventor, are discussed next. These are devices in which negative resistance is obtained as a *bulk* property of the material used, rather than a junction property. Gunn diodes are now very common medium-power oscillators for microwave frequencies, with a host of applications that will be covered.

Another class of power devices depends on *controlled avalanche* to produce microwave oscillations or amplification. The *IMPATT* and *TRAPATT* diodes are the most commonly used, and both are discussed in the next section of the chapter. They are followed in the next-to-last section by an explanation of the *Schottky barrier* and *PIN diodes*, used for mixing/detection and limiting/switching, respectively.

The final topic covered is the amplification of microwaves or light by means of the quantum-mechanical effect of stimulated emission of radiation. The topic covers masers, lasers and a number of other optoelectronic devices.

OBJECTIVES

Upon completing the material in Chapter 12, the student will be able to:

Understand the theory and application of stripline and microstrip circuits and SAW devices.

Explain the construction, limitation, and performance characteristics of microwave integrated circuits, transistors, and diodes.

Define the term *maser*.

Discuss the differences between masers and lasers.

12-1 PASSIVE MICROWAVE CIRCUITS

Transmission lines and waveguides were invented at the time of, and used in conjunction with, microwave electron tubes such as those discussed in the preceding chapter. They are still so used at medium and high powers. Again, being low-loss, they are used at low powers where significant distances are traversed, as in connecting antennas to receivers. However, transmission lines are considerably bulkier than semiconductor microwave devices, and consequently their use would prevent the reduction in circuit size and weight which would otherwise be obtainable. *Stripline* and *microstrip* have been developed and are used for circuit interconnections with solid-state devices. They may also be used for passive components, as can another class of devices, using SAW principles. *Microwave integrated circuits* (MICs) are not uncommon and have many applications.

12-1.1 Stripline and Microstrip Circuits

Stripline and *microstrip* are physically related to transmission lines but are covered here because they are microwave circuits used in conjunction with semiconductor

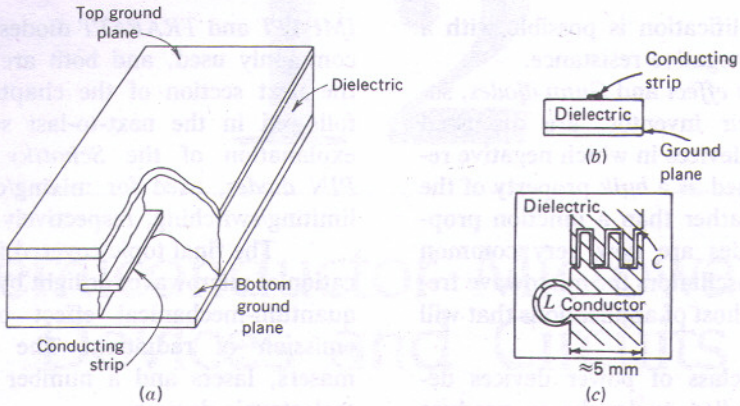

FIGURE 12-1 **(*a*) Stripline; (*b*) microstrip cross section; (*c*) microstrip *LC* circuit.**

microwave devices. As illustrated in Figure 12-1, *stripline* consists of flat *metallic ground planes*, separated by a thickness of dielectric in the middle of which a thin metallic strip has been buried. The conducting strip in *microstrip* is on top of a layer of dielectric resting on a single ground plane. Typical dielectric thicknesses vary from 0.1 to 1.5 mm, although the metallic strip may be as thin as 10 μm.

Stripline and microstrip were developed as an alternative conducting medium to waveguides and are now used very frequently in a host of microwave applications in which miniaturization has been found advantageous. Such applications include receiver front ends, low-power stages of transmitters and low-power microwave circuitry in general.

Stripline is evolved from the coaxial transmission line. It may be thought of as flattened-out coaxial line in which the edges have been cut away. Propagation is similarly by means of the TEM (transverse electromagnetic) mode as a reasonable approximation. Microstrip is analogous to a parallel-wire line, consisting of the top strip and its image below the ground plane. The dielectric is often Teflon, alumina or silicon. It is possible to use several independent strips with the same ground planes and dielectric, for both types of circuits. Semiconductor microwave devices are often packaged for direct connection to stripline or microstrip.

As was shown in Chapter 10, waveguides are used not only for interconnection but also as circuit components. The same applies to stripline and microstrip (and indeed to coaxial lines). Figure 12-1*c* shows a microstrip *LC* circuit—typical capacitances possible are up to 1 pF, and typical inductances up to 5 nH. The stripline version would be very similar, with just a covering of dielectric and a second ground plane. Transformers can be made similar to the single-turn coil shown, and passive filters and couplers may also be fabricated. Resistances are obtained by using a patch of high-resistance metal such as Nichrome, instead of the copper conductor. Ferrite may be readily blended into such circuits, and so isolators, circulators and duplexers (all described in Chapter 10) are quite feasible. Figure 10-43 shows the construction of a ferrite stripline circulator.

Microstrip has the advantage over stripline in being of simpler construction and easier integration with semiconductor devices, lending itself well to printed-circuit and thin-film techniques. On the other hand, there is a far greater tendency with microstrip to radiate from irregularities and sharp corners. Thus there is a lower isolation between adjoining circuits in microstrip than in stripline. Finally, both Q and power-handling ability are lower with microstrip.

In comparison with waveguides (and coaxial lines), stripline has two significant advantages; reduced bulk and greater bandwidth. The first of these goes without saying, while the second is due to a restriction in waveguides. In practice, these are used over the 1.5:1 frequency range, limited by cutoff wavelength at the lower end and the frequency at which higher modes may propagate at the upper end. There is no such restriction with stripline, and so bandwidths greater than 2:1 are entirely practicable. A further advantage of stripline, as compared with waveguides, is greater compatibility for integration with microwave devices, especially semiconductor ones. On the debit side, stripline has greater losses, lower Q and much lower power-handling capacity than waveguides. Circuit isolation, although quite good, is not in the waveguide class. The final disadvantage of stripline (and consequently of microstrip) is that components made of it are not readily adjustable, unlike their waveguide counterparts.

Above about 100 GHz, stripline and microstrip costs and losses rise significantly. However, at frequencies lower than that, these circuits are very widely used, particularly at low and medium powers.

12-1.2 SAW Devices

Surface acoustic waves may be propagated on the surfaces of solid piezoelectric materials, at frequencies in the VHF and UHF regions. Devices employing SAW principles were first discussed in the late 1960s, then moved out of the laboratory in about 1974, and since about 1978 have found many applications as passive components in the low microwave range.

The application of an ac voltage to a plate of quartz crystal will cause it to vibrate and, if the frequency of the applied voltage is equal to a mechanical resonance frequency of the crystal, the vibrations will be intense. Because quartz is piezoelectric, all mechanical vibrations will be accompanied by electric oscillations at the same frequency. The mechanical vibrations can be made very stable in frequency, and consequently piezoelectric crystals find many applications in stable oscillators and filters. As the desired frequency of operation is raised, so quartz plates must be made thinner and thus more fragile, so that crystal oscillators are not normally likely to operate at fundamental frequencies much in excess of 50 MHz. It is possible to multiply the output frequency of an oscillator almost indefinitely (see also Section 12-3.3), but inconvenience would be avoided if multiplication were unnecessary. This may be done with SAW resonators, which employ thin lines etched on a metallic surface electrodeposited on a piezoelectric substrate. The etching is performed by using photolithography or electron beam techniques, while the most commonly used piezoelectric materials are quartz and lithium niobate.

A simplified sketch of a typical interdigitated SAW resonator is shown in Figure 12-2. Traveling waves in both directions result from the application of an RF voltage