SOLID-STATE DEVICES FOR 1 GHz

New frontier for experiments. Solid-state devices let you explore the 1 GHz region and beyond.

JOSEPH J. CARR

Part 2 USING SOLID-STATE DEvices to generate microwave signals required solving some complex problems. This month we'll continue our look at the development of those devices.

Gunn oscillators

The Gunn device will oscillate in the transit-time mode using only a simple resistance for the load. The efficiency in that mode, however, is only one- to five-percent, so relatively large amounts of DC power are required to generate small amounts of RF power.

If we place the Gunn device inside a resonant cavity, and bias the device for the delayed transit-time mode, then we will obtain better efficiency and some flexibility of the operating frequency.

Figures 8 and 9 show two methods for mounting a Gunn device inside a resonant cavity. Figure 8 shows a cutaway view of a coaxial cavity. The cavity is one-half of a wavelength long, while the base of the Gunn device is placed at the one-eighth wavelength point. A conductive "dowel" supports the Gunn device and connects it to the ends of the cavity; the dowel is also the center conductor of the coaxial cavity.

A tuning screw is used to vary the operating frequency of the device. It effectively changes the dimensions of the cavity, and can fine tune the operating frequency over a small range.

The oscillations on the inside of the cavity are coupled to the outside world through a short coupling loop that is situated parallel to the dowel center conductor. The load impedance of the Gunn device is set by the position of the coupling loop, and is adjusted for the best compromise between the stability of the operating frequency and the maximum output power.

While simple, the coaxial cavity suffers from a few basic problems. It is a low-Q tank, and is sensitive to factors such as temperature and load impedance variations. The Gunn device in a coaxial cavity may also tend to oscillate on a harmonic of the tank frequency.

A rectangular waveguide can also be used as a tuned cavity if one end is blocked off and the Gunn device is placed at the one-eighth wavelength point as shown in Fig. 9. The DC bias is provided to the Gunn device through an RF choke that is designed to block the microwave RF.

The dimensions of the cavity are determined by the placement of a partition. Energy from the cavity is coupled into the waveguide-transmission line through an opening called an *iris*. The size of that iris is a trade-off between

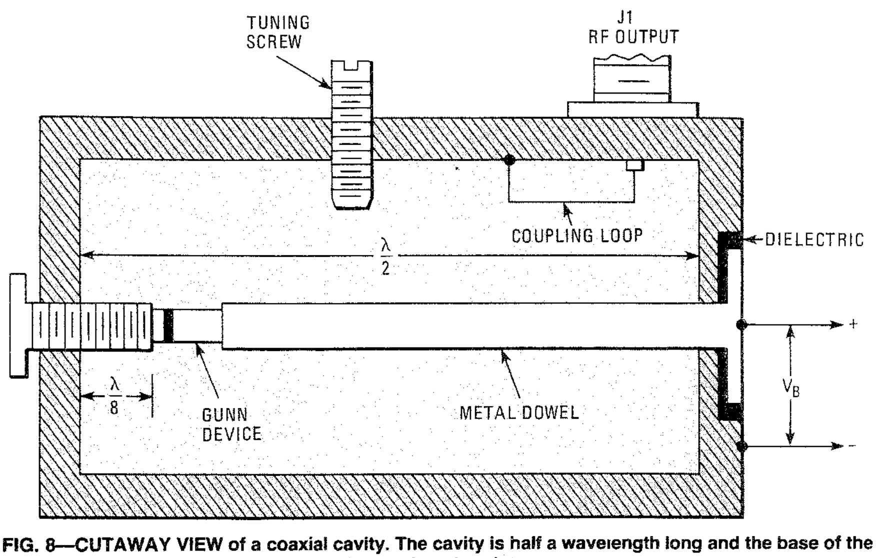

FIG. 8—CUTAWAY VIEW of a coaxial cavity. The cavity is half a wavelength long and the base of the Gunn device is placed at the one-eighth-wavelength point.

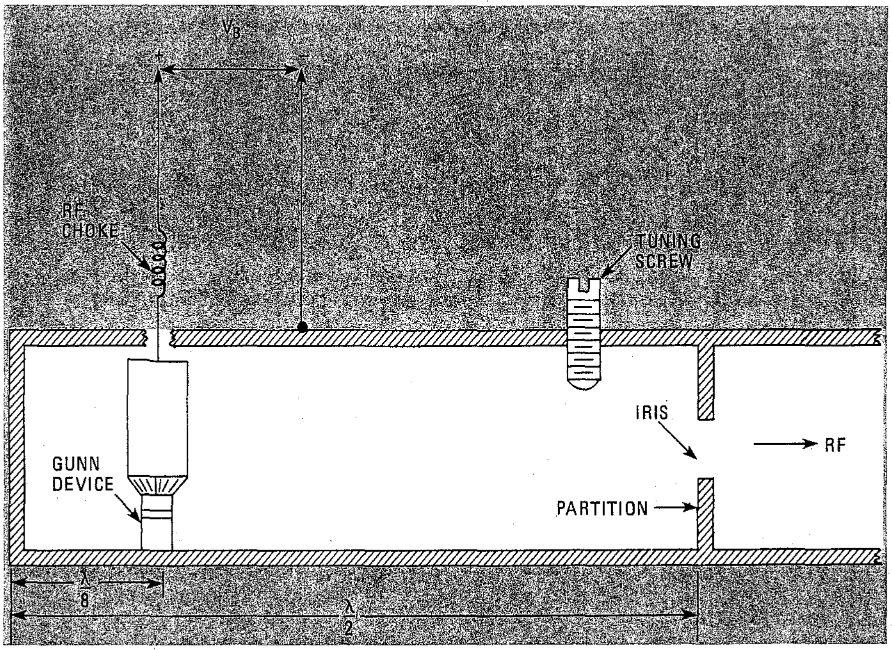

FIG. 9—RECTANGULAR WAVEGUIDE used as a tuned cavity. The DC bias is provided to the Gunn device through an RF choke designed for microwave use.

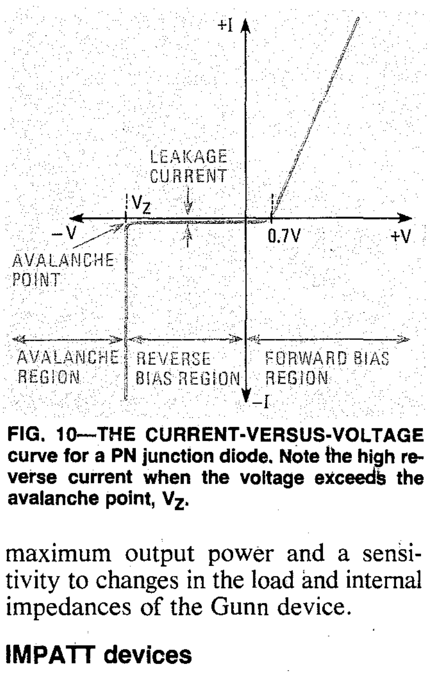

FIG. 10—THE CURRENT-VERSUS-VOLTAGE curve for a PN junction diode. Note the high reverse current when the voltage exceeds the avalanche point, V_Z.

maximum output power and a sensitivity to changes in the load and internal impedances of the Gunn device.

IMPATT devices

The IMPATT (*IMP*act *A*valanche *T*ransit *T*ime) diode was proposed in 1953 by W.T. Read of Bell Laboratories. Read's suggestion was that the phase delay in a PN junction diode between an applied RF voltage and an avalanching current could be used for negative resistance operation at microwave frequencies. In Read's model diode, carriers drifting through a depletion region cause the negative resistance. Fabrication difficulties prevented the construction of a working Read diode until the mid-60's. In 1965, however, R.J. Johnson of Bell Labs verified the validity of Read's model when he generated approximately 80 milliwatts of RF energy at 12 GHz from a silicon PN junction diode. Read's diode depends upon impact avalanche and transit-time phenomena, so was given the acronym IMPATT. It has now been recognized that Read's structure is just one of several that will result in IMPATT operation.

Figure 10 shows the current-vs-voltage curve for a PN-junction diode. For our present purposes we will consider only operation in the reverse-bias region, i.e., the region in which *V* is less than zero. There is a critical breakdown voltage V_Z in the reverse bias region. At reverse potentials less than this value, the current through the PN junction is a very small leakage current. But the current suddenly increases when the voltage exceeds V_Z: the junction is operating in avalanche. The increased current is due to secondary emission or avalanche multiplication, in which electrons of the leakage current have a high probability of colliding with other electrons. The result is a very rapid increase in reverse current. In ordinary signal or rectifier diodes, the avalanche phenomenon can be destructive. Certain types of diodes, however, are able to control the avalanche process by using properly doped semiconductor material. Zener diodes and controlled avalanche rectifiers are in that category.

Consider the IMPATT diode structue shown in Fig. 11. The PN junction of interest is on the left side of the structure. Note that the right hand contains an n-n+ junction. The n+ region forms a contact of low resistivity for the electrode, and prevents metallic ion migration (much as in the Gunn structure) into the active region.

The center region is made up of n-type material and is the active zone. That active region must be doped to the extent that it is fully depleted at breakdown. We want to insure that a very small electrical field will cause velocity saturation of the electrons.

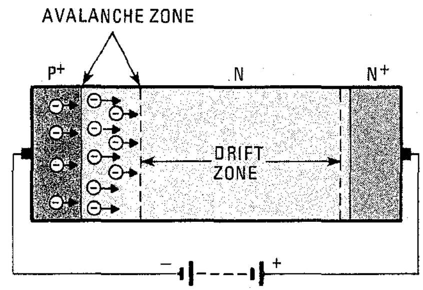

FIG. 11—IMPATT DIODE structure. Electrons generated in the avalanche zone will flow into the drift zone of the n-region.

The electrons generated in the avalanche zone of the IMPATT diode shown in Fig. 11 will flow into the drift zone of the n-region. It takes very little added voltage to cause a large increase in current in that mode.

Let's consider a situation where an IMPATT device is biased to a potential just below V_Z; i.e., in the reverse-bias region but not quite to the avalanche point. We must select such a bias that a small added potential will throw the device into the avalanche region. Let us further assume that the IMPATT device is operated in parallel with a high-Q resonant tank circuit (i.e., the IMPATT device is operated inside of a resonant cavity). The reverse-biased PN junction will create a noise signal that shock-excites the tank circuit into oscillation. The RF voltage produced by the resonant tank is added to the bias voltage, causing the diode to go into the avalanche mode on positive peaks of the cycle.

The number of electrons generated by avalanche multiplication is a function of the applied voltage (Fig. 12-a) and the number of charge carriers present. Because of that dual dependence, the avalanche current pulse (Fig. 12-b) continues to increase even after the RF voltage cycle has passed its peak. During that process the charge density at the avalanche point grows exponentially while the avalanche charge current (Fig. 12-c) drifts toward the other end of the drift zone.

Does the IMPATT produce negative resistance? Note that the current reaches a peak (Fig. 12-c) as the sine-wave RF voltage goes through its zero crossing point (Fig. 12-a); a 90-degree delay with respect to the voltage peak. The criterion for negative resistance is a phase difference of 90 degrees or more between the applied voltage and the series current, so we may conclude that the IMPATT is a negative-resistance device.

The pulse current in the external tank circuit (Fig. 12-d) is semi-square and represents a current lag over applied voltage of more than 90 degrees. Those two factors are shown together in Fig.

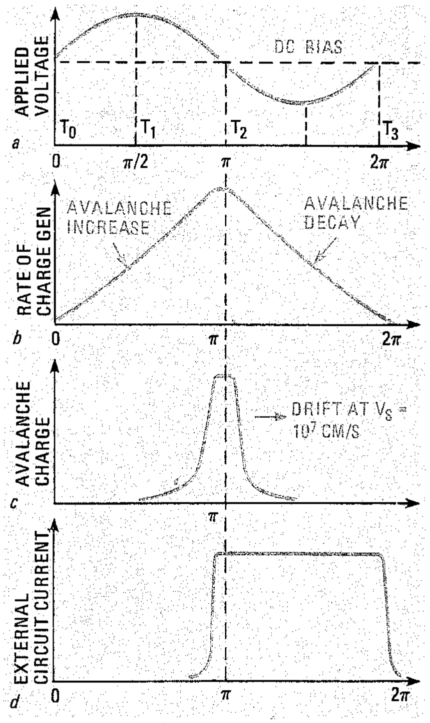

FIG. 12—AVALANCHE CURRENT pulse (b) continues to increase even after the RF voltage cycle has reached its peak (a).

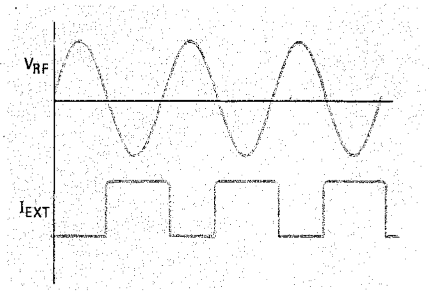

FIG. 13—THE PULSE CURRENT in the external tank circuit is a semi-squarewave and lags the applied voltage by more than 90 degrees.

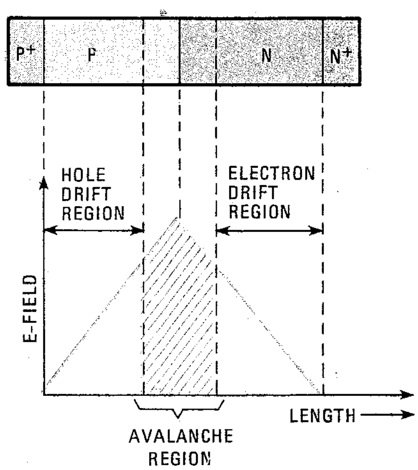

FIG. 14—DOUBLE-DRIFT IMPATT device. In this device the avalanche region brackets the PN junction.

13. Two factors combine to cause the positive external current during the negative excursions of the RF waveform: the time delay of the avalanche process and the drift time of the avalanche charge. Instead of absorbing energy, in the manner of a positive, or ohmric, resistance, the IMPATT offers a negative resistance.

The IMPATT device just described is known as a *single-drift* device. But an avalanching PN junction produces both kinds of charge carriers; i.e., holes and electrons. The single-drift IMPATT uses only the electrons, and returns the holes to the cathode p-region. That fact limits the efficiency of the single-drift devices to less than 15 percent.

Greater efficiency is obtained through the use of a *double-drift* IMPATT device, such as shown in Fig. 14. That is a p^+-p-n-n^+ structure in which the avalanche region brackets the PN junction. The p+ zone serves as an ohmic contact for hole charge-carriers, while the n^+ region serves the same purpose for electrons. The output efficiency is increased over that of the single-drift variety because the holes drift across the p-zone very nearly in phase with the electrons drifting across the n-zone.

IMPATT applications

The previous discussion has demonstrated that the IMPATT device will function as an oscillator at microwave frequencies. If an IMPATT is placed inside of a high-Q resonant cavity, and biased with a DC potential slightly below the avalanche potential, then noise pulses will ring the cavity to produce the RF sinewave that actually drives the junction into the IMPATT mode of oscillation. IMPATT operation occurs because the voltage of the ringing waveform (an RF signal) adds algebraically with the DC bias, causing the junction to go into the avalanche mode on peaks of the RF cycle. If the device is correctly biased, then, the junction will be in the avalanche condition for most of the positive half of the RF sinewave excursion.

Although the IMPATT device is an oscillator that is capable of producing substantial peak-pulse powers at microwave frequencies, it is not universally applied because it is a noisy source (avalanching is a noisy process). For that reason, one does not ordinarily see IMPATT's as receiver local oscillators.

IMPATT's are used primarily at frequencies above 3 or 4 GHz, with frequencies up to 100 GHz having been obtained. Many high-power IMPATT's require operating potentials between 75 and 150 volts DC; a fact seen as a disadvantage by some. Also, IMPATT's are usually operated from constant-current power supplies, also a disadvantage.

The applications of the IMPATT are not limited to oscillator service. There is one report of IMPATT's being used as microwave frequency multipliers. Many IMPATT's are used as amplifiers. In fact, it has been claimed that most IMPATT applications are as amplifiers, not as oscillators. IMPATT amplifiers

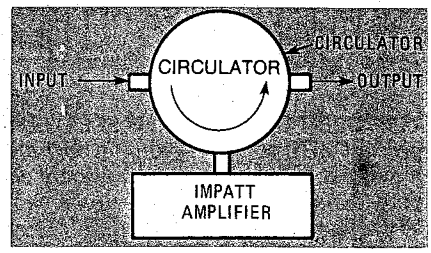

FIG. 15—IMPATT AMPLIFIERS have just one port and must be coupled to a circulator.

have only one port, so must be coupled to a *circulator* to isolate input and output ports of the amplifier as shown in Fig. 15. That type of amplifier is called a *reflection amplifier*.

TRAPATT diodes

IMPATT diodes are generally limited to operation at frequencies above 3 or 4 GHz. The problem of lower operating frequencies is one of finding a method for stretching the duration of the transit time. Until 1967, it had proven difficult to use solid-state devices to generate any significant amount of power in the 1-GHz region. In 1967, however, engineers working for RCA succeeded in exciting an IMPATT-like device into a different mode of operation. One set of trials produced pulse powers of 425 watts with an efficiency of 25 percent. Further work with that new mode yielded efficiencies up to 60 percent, with later work producing efficiencies as high as 75 percent. Tuned tank circuits developed at RCA in that era permitted a tuning range that was continuous over 0.9 to 1.5 GHz.

It appeared that the problem of increasing the transit time had been solved, but no one really knew why! At the time the basic work on the TRAPATT device was going on there was no good theory that explained the observed behavior. Workers at RCA dubbed the new mode the *anomalous mode,* perhaps reflecting the fact that they had no theory of operation.

At least two different theories were advanced to explain the behavior of the anomalous mode. Bell Laboratories advanced the theory that the high efficiency and lowered frequency of operation was explained by the fact that a trapped plasma was created in the device between sweeps of the IMPATT mode of operation. The theory held that the trapped plasma shielded the charge carriers from the external voltage field, causing them to drift out of the plasma at low velocity. That theory led to the acronym by which the device is now known: TRAPATT (*TRA*pped *P*lasma *A*valanche *T*ransit *T*ime).

Next month we'll finish discussing the TRAPITT diode and show you how it and the IMPATT are related. We'll conclude this three-part series with a look at the BARITT device. **R-E**