Progress with CW IMPATT Diode Circuits at Microwave Frequencies

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Invited Paper

***Abstract*—Progress with CW operation of IMPATT diodes at frequencies up to 20 GHz is reviewed, with emphasis on their circuit applications. Noise properties, stability criteria, and reliability are discussed. Comparisons are made between flat-profile and modified-Read-profile diodes. Examples of oscillator and amplifier circuits are presented.**

I. Introduction

THE IMPATT DIODE (or avalanche diode) is a device which combines avalanche breakdown and majority carrier transit time to produce a negative resistance at microwave frequencies. First proposed by Read in 1958 [1], initial results were disappointing because the prescribed doping profile was beyond the state of the art of silicon technology at the time. In 1965, DeLoach [2] found that a simple p-n junction diode of appropriate design could demonstrate the same negative resistance effect.

Since that time progress has been rapid. The use of diamond as a heat sink [3], [4], and the use of plated heat sinks [5] have both permitted high CW powers to be achieved. With watts of power available from a single device, circuits have been designed to allow replacement of traveling-wave tubes in transmitter applications.

More recently [6], modified-Read-profile diodes have been studied extensively. These diodes have achieved efficiencies of 20–36 percent, compared with the 6–15 percent for flat-profile diodes.

This paper will review progress with CW IMPATT diodes, with a particular emphasis on their circuit applications. For further study of the diode properties, three excellent review papers are recommended [7]–[9].

Since performance above 20 GHz is included in another paper [10], only operation below 20 GHz will be discussed.

II. Diode Output Power and Efficiency

Typical doping and electric field profiles for IMPATT diodes are shown in Fig. 1. The modified Read profiles are of two basic types, Hi–Lo, shown in Fig. 1(b), and Lo–Hi–Lo, shown in Fig. 1(c). Observe that the high-field (avalanche) region of the modified Read's is confined to a shorter distance as compared with that for the flat-profile diode, resulting in a lower dc voltage for the same frequency of operation. Separate optimization of the electric fields in the avalanche and drift regions optimize electron bunching and dc voltage for high efficiency.

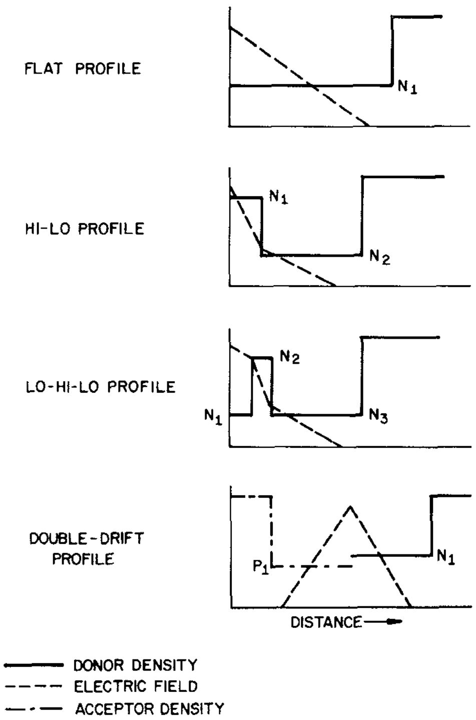

Fig. 1. IMPATT diode doping profiles and resulting electric field distributions.

Flat-profile diodes have been made using germanium, silicon, and gallium arsenide. Only Si and GaAs diodes are used today, and modified Read diodes are made only in GaAs. GaAs is preferred today for operation below 20 GHz because of its higher efficiency and lower noise performance.

The profiles of Fig. 1(a), (b), and (c) are for single-drift designs with Schottky-barrier contacts. Some double-drift diodes have also been made, as shown in Fig. 1(d), wherein electrons and holes flow in opposite directions away from the avalanche region. Double-drift diodes have higher RF impedance levels and higher values of thermal impedance for comparable areas. DC voltages are nearly

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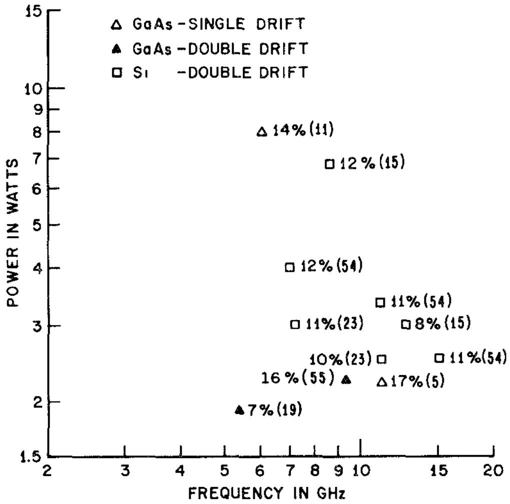

Fig. 2. Performance realized from flat-profile IMPATT diodes up to 1978. Efficiencies in percent and the reference for each result are also given.

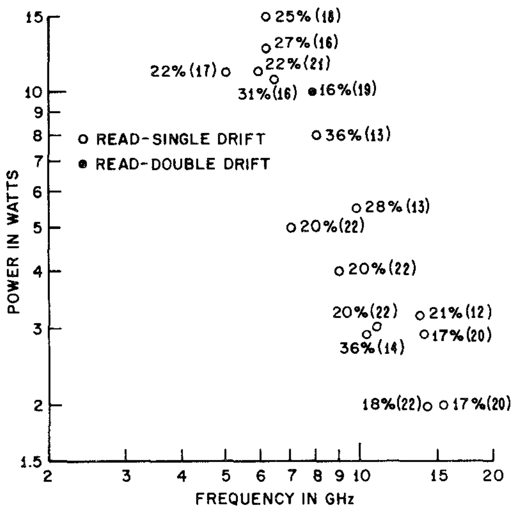

Fig. 3. Performance realized from modified-Read-profile diodes up to 1978. Efficiencies in percent and the reference for each result are also given.

twice those of single-drift diodes. In addition to Schottky-barrier contacts, p-n junctions have also been used for flat-profile and modified Read diodes.

Measured output power data are presented in Figs. 2 and 3 [5], [11]–[23], [54], [55]. Values of dc-to-RF conversion efficiency are also shown. The number in parenthesis gives the reference for the corresponding point. Efficiencies of 6–10 percent are typical for flat-profile Si diodes, 10–15 percent for flat-profile GaAs diodes, and 20–36 percent for modified Read diodes. Relatively little effort has been devoted to developing double-drift GaAs diodes, so the experimental results may not be representative of ultimate performance limits. These data are for single-package diodes only. Diodes may be connected in series, parallel, or hybrid coupled to produce higher output powers. The resulting power outputs are sufficiently high for most communication applications.

III. Noise Performance

Noise measure is a useful way of characterizing the noise performance of an IMPATT diode. It is defined as the ratio (in decibels) of the device noise temperature to the standard noise temperature 290 K. It is useful because it is an intrinsic property of the device, whereas noise characteristics such as carrier-to-noise ratio are affected by circuit parameters (such as oscillator Q).

For small-signal operation, noise measure is uniquely defined. However, for large-signal operation, the FM noise measure M_{FM} and the AM noise measure M_{AM} may be slightly different. Each is defined so as to express the noise contribution in a system having the corresponding modulation scheme.

For FM system use, the following relationships are useful [24]. For a free-running oscillator

$$\Delta f_{rms} = \left(\frac{f_o}{Q_{ext}}\right)\sqrt{\frac{kT_0 M_{FM} B}{P_o}} \tag{1}$$

where

Δf_{rms}	rms frequency fluctuation,
f_o	oscillation frequency,
Q_{ext}	external circuit Q,
k	Boltzmann's constant,
T_0	290 K,
B	noise bandwidth,
P_o	RF output power.

For a locked oscillator, where the locking signal has negligible noise

$$\Delta f_{rms} = f_m\sqrt{\frac{kT_0 M_{FM} B}{P_s}} \tag{2}$$

where f_m is the frequency separation from the carrier and P_s is the locking signal power. Finally, for a high-gain amplifier the FM noise figure is approximately equal to M_{FM}. This relationship holds for both stable amplifiers and locked oscillators.

Noise measure varies with RF level [25], [26]. Data for typical diodes are shown in Fig. 4. The flat-profile diodes exhibit considerable variation of noise measure with RF level. On the other hand, the noise measure of the modified Read diode is nearly constant [27]. Thus for best noise performance flat-profile GaAs IMPATT's are used for the low-level stages of a multistage amplifier (Gunn devices and transistors are also used).

IV. Circuit Design Principles

A. Basic Design Considerations

The negative conductance of a flat-profile IMPATT diode is typically a monotonically decreasing function of the RF voltage as in Fig. 5 [28]. Thus in an oscillator, the level of oscillation is determined by the load conductance presented to the diode.

Amplifiers are generally constructed using a circulator to connect the input and output signals to the IMPATT

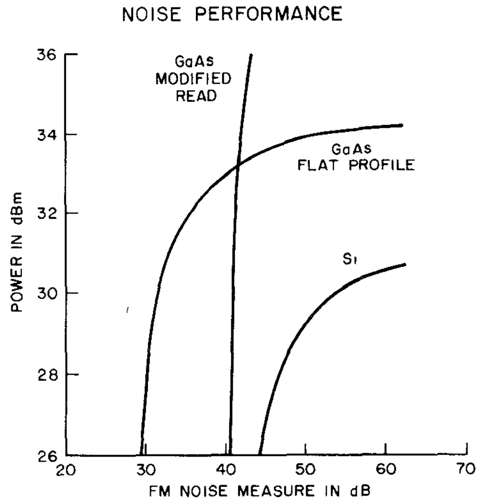

Fig. 4. Typical noise performance of IMPATT diodes.

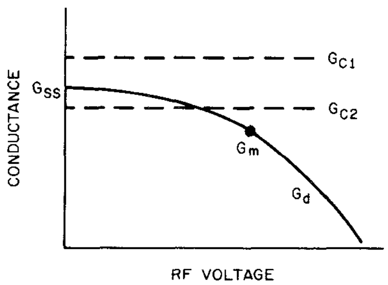

Fig. 5. Negative conductance versus RF voltage for operation in the IMPATT mode.

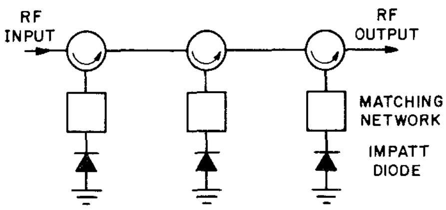

Fig. 6. Typical configuration for an IMPATT amplifier.

diode. The circuit conductance presented to the diode is adjusted by appropriate matching circuitry. If this conductance is less than or equal to G_{SS}, the small-signal value, the circuit functions as a locked oscillator. Otherwise, it is a stable amplifier. Locked oscillators are often used for high-gain FM applications, since it is difficult to obtain high-gain stable amplification over a range of temperatures.

A typical amplifier configuration is shown in Fig. 6. The gain of a stage (at center frequency) is given by

$$\text{gain} = \left[\frac{G_c + G_d}{G_c - G_d} \right]^2 \tag{3}$$

where G_c is the circuit conductance presented to the diode and G_d is the magnitude of the diode negative conductance at the operating RF level.

Alternatively, the gain is also given by

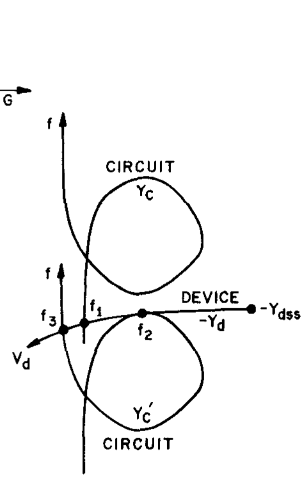

Fig. 7. Graphical determination of the operating point for an IMPATT diode connected to a circuit admittance having a loop. The circuit loci illustrate two different tuned conditions.

$$\text{gain} = \frac{P_{\text{in}} + P_{\text{add}}}{P_{\text{in}}} = 1 + \frac{P_{\text{add}}}{P_{\text{in}}} \tag{4}$$

where P_{in} is the RF input power and P_{add} is the RF added power.

When designing a power amplifier, it is desirable to design so that the power stages each add the maximum generated power capability[1] of the diode. Thus in Fig. 6, the second and third stages may be so designed. Their gain values would then be determined by (4). Maximum generated power[1] corresponds to a specific value of diode negative conductance, e.g., G_m in Fig. 5. With gain specified by (4), G_c is determined from (3). If the gain is low, G_c will have a value G_{c1} giving a stable amplifier (Fig. 5). On the other hand, if the required gain is high, G_c could have a value G_{c2} corresponding to a locked oscillator.

Both stable amplifiers and locked oscillators are used in IMPATT amplifiers. When locked oscillators are used, provision is usually made in the power supply to remove dc power when the locking signal is too weak for proper operation [29].

B. Circuit Impedance Loops

In free-running oscillators or locked oscillators, one must be careful to design the circuit to avoid impedance (or admittance) loops [30]. Consider the complex admittance plane plot of circuit admittance Y_c shown in Fig. 7. The negative of the diode admittance Y_d is also plotted with RF level as the variable. The intersection of the circuit and device curves determines the frequency f_1 and level of oscillation. Now suppose the circuit is tuned to a higher frequency. The circuit-admittance locus moves downward. When the circuit-admittance trace moves to the position denoted Y_c', the frequency will suddenly jump from f_2 to f_3 and the RF level will also jump. A similar

[1]Rather than a true maximum, this is usually a nominal level guaranteed by the diode supplier.

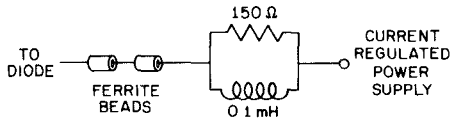

Fig. 8. Bias circuit designed to prevent low-frequency oscillations.

jump will occur when tuning back down to f_1 as the circuit-admittance locus moves upward. These hysteresis effects should be avoided by proper circuit design. That is, circuit-admittance (or impedance) loops should be avoided in oscillators.

Note, however, that such loops are often used in a broad-band stable amplifier design. In this case, the circuit and device curves never intersect, and the above effect does not occur.

C. Low-Frequency Oscillations

The above effect can occur with any negative resistance device. We next discuss several effects which are peculiar to IMPATT diodes.

When operating at large signal levels, a dc rectification effect gives rise to low-frequency negative resistance [31]. This effect has been observed up to frequencies as high as 1 GHz. Values have been measured ranging from 12 Ω for Si diodes up to 122 Ω for GaAs diodes. The usual symptom is the appearance of sidebands symmetrically located around the carrier as viewed on a spectrum analyzer. If these oscillations become severe enough, they can result in diode failure.

These oscillations are prevented by designing the circuit to provide high resistance at low frequencies. An example of an effective bias circuit is shown in Fig. 8. The ferrite beads present high series resistance at frequencies in the 10–500-MHz range. The *RL* circuit assures high series resistance from 1 to 10 MHz, and the constant-current power supply provides high output impedance at lower frequencies. In addition, one must design the microwave circuit so as to minimize shunt capacitance. Such capacitance reduces the effective series resistance seen by the diode. Also, the microwave circuit should provide high resistance in the frequency range 500–1000 MHz. The last requirement often requires experimental optimization, because of the distributed effects in a complex circuit.

D. Subharmonic and Other Parametric Oscillations

Because of the variable-reactance nature of the avalanche effect, IMPATT diodes are also prone to parametric oscillations, the subharmonic oscillation being particularly troublesome. These oscillations are pumped by the desired RF signal. Strong oscillations of this type can reduce the power available at the desired frequency and also contribute to excess noise. Greater than 40 dB of excess noise has been observed near the threshold of such an oscillation.

This effect has been studied, and circuit criteria have been derived to avoid these oscillations [32], [33]. Low resistance at the subharmonic prevents subharmonic oscillations, but the requirements for parametric frequencies are more complicated and require a detailed analysis. With care, a circuit can be synthesized which is unconditionally stable [34].

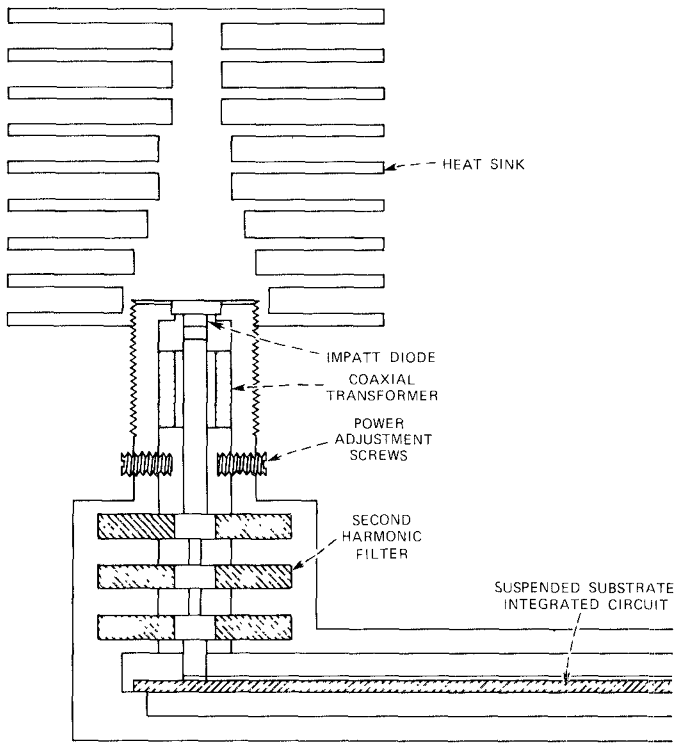

Fig. 9. IMPATT oscillator circuit.

E. Second-Harmonic Effects

Second-harmonic tuning effects in IMPATT diodes have been studied in great detail [35]. Generally, they are troublesome and should be avoided. Second-harmonic resonances produce ripple in the power versus frequency characteristic, and have also been observed to produce hysteresis effects in oscillator-tuning characteristics. These effects are minimized by preventing the diode from seeing high impedances at second-harmonic frequencies.

F. A Case History

In high-power IMPATT amplifier development, considerable effort is often spent eliminating spurious oscillations. It may be of some interest to review a particular case history.

The first IMPATT amplifier used in the Bell System was a 1-W 6-GHz locked oscillator, which uses a flat-profile Si IMPATT diode [29]. The oscillator portion of the circuit is shown in Fig. 9. The suspended substrate circuit contains the circulator, bias circuit, monitor circuits, etc. The frequency of oscillation was tuned by sliding the quarter-wave coaxial transformer up and down. The power adjustment screws varied shunt capacitance at a point on the line which, when referred to the diode, produced a change in the real part of the impedance seen by the diode. These screws are adjusted to produce an output power of 1 W.

The second-harmonic band-stop filter was included for two reasons. First, by controlling the phase of the second-harmonic reflection and keeping it close to the diode it was felt that ripples in the power versus frequency characteristic could be controlled. Second, the filter prevented second-harmonic energy from causing an error in the detected power of an input-signal monitor circuit.

The first spurious oscillation observed during development consisted of 60-MHz sidebands symmetrically located about the carrier. The bias circuit had a lumped 47-Ω resistor in series, but stray shunt capacitance was apparently reducing the effective resistance at 60 MHz [31]. This problem was eliminated by adding several ferrite beads on the bias lead between the resistor and the microwave circuit.

Next, it was observed that some amplifiers exhibited power and frequency hysteresis effects as they were tuned in frequency. The frequency could jump by 40–80 MHz. It was first thought that this might be a symptom of a circuit impedance loop [30]. Although the circuit impedance trace (as measured on a network analyzer) did not show such a loop, it was thought that the diode package parasitics might introduce a loop as viewed by the diode wafer. Kurokawa performed an experiment to rule out this hypothesis. He operated the diode at reduced current, below the oscillation threshold, and plotted small-signal gain versus frequency. This characteristic showed the typical single-tuned response, maximum gain at the center frequency with monotonic gain falloff at higher and lower frequencies. From this it was inferred that the diode wafer saw a circuit impedance free of loops.

Further experiments finally revealed the cause of the frequency jump. A subharmonic oscillation was the culprit. The frequency jump occurred coincident with the onset or dropout of a subharmonic oscillation. It is difficult to observe the subharmonic because it is below the cutoff frequency of the input and output waveguides of the amplifier. It was observed using a probe into the coaxial section. The subharmonic oscillation was eliminated by modifying the impedance seen by the diode at the subharmonic frequency. A 50-Ω resistor in series with a half-wave open-circuited stub was connected to the circuit on the suspended substrate. At 6 GHz the half-wave stub prevents the resistor from shunting the circuit. However, at 3 GHz the stub is a quarter-wavelength long, and it results in a shunt resistance of 50 Ω. This resistor was located at a point along the line so as to reduce the impedance seen by the diode at the subharmonic frequency to approximately 10 Ω, which eliminated the subharmonic-oscillation problem.

As additional amplifiers were constructed using diodes with a wider range of parameters, another problem arose. A frequency jump appeared during tuning which was not due to the subharmonic. Probing of the coaxial line revealed a large change in second-harmonic energy associated with the frequency jump. In hindsight, it was realized that an instability of this type had been predicted theoretically by Brackett [35]. The effect was eliminated by using dielectric loading in the coaxial line to shift the phase of the reflection from the second-harmonic band-stop filter.

With these modifications, more than 800 amplifiers were produced without further problems of spurious oscillations. Later, the tuning mechanism was modified slightly to use a flat-profile GaAs diode. This substitution was made without any new problems of spurious oscillations.

G. Premature Collection Mode

We next discuss an effect which is peculiar to the modified Read diode, the premature collection (PC) mode [36]. The modified Read diode can operate in the normal IMPATT mode with typical efficiences of 20–30 percent. However, at high RF levels and at the higher frequency end of the band a different mode (PC) is possible which predicts efficiencies up to 40 percent.

The PC mode is a large-signal effect associated with the RF modulation of the depletion width of the device. The transit time of the carriers through the drift region can be reduced significantly if the timing is such that they reach the end of the depletion region when the depletion width is at a minimum. Because of the shorter transit time, the frequency is higher. But the important effect is that the efficiency of this process can be much higher than that for the normal IMPATT mode.

The variation of negative conductance versus RF voltage for a modified Read diode is shown in Fig. 10 for a frequency high enough to exhibit the PC mode. At the higher RF voltages, the enhanced efficiency of the PC mode gives rise to a region of high values of negative conductance.

Consider the effect of circuit tuning for an oscillator, where the load conductance is being varied [37]. For G_{c1} generated power corresponds to point 1. As the load conductance is reduced, the operating point moves successively to points 2 and 3. However, with further reduction in load conductance, operation will suddenly shift to point 4, resulting in a sudden increase in generated power. Increasing the load conductance from this point moves the operation to point 5, where the output power and efficiency are maximized. Similar hysteresis effects can occur for fixed tuned conditions when the dc is being varied.

The plot of Fig. 10 is for constant dc. The large RF voltage of the PC mode causes the diode dc voltage to be reduced to a value of the order of 75 percent of the breakdown voltage. Consider the design of a high-power low-gain amplifier stage. Suppose the desired gain prescribed a load conductance G_{c1} for efficient operation in the PC mode. This would permit oscillations at point 1 to occur. This can be avoided by using a biasing scheme

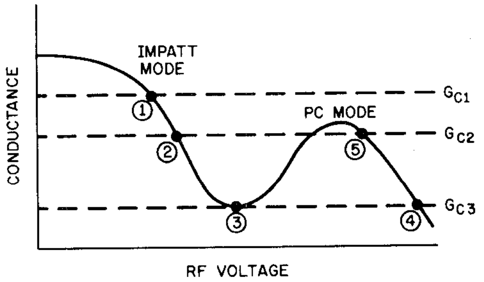

Fig. 10. Negative conductance for a modified Read diode at frequencies high enough to exhibit the premature-collection mode.

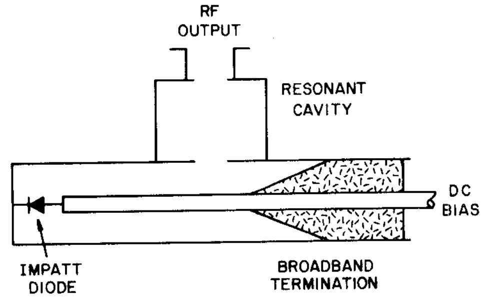

Fig. 11. Basic oscillator circuit which achieves stability by broad-band matching.

different from the usual constant current source [38]. If a voltage source in series with a resistance is used, then the dc can be made low for small RF signals but will be considerably larger for large RF signals corresponding to the PC mode. This occurs because of the large drop in diode dc voltage for the PC mode. Values of resistance and dc supply voltage can be chosen so that the small-signal negative conductance is less than G_{c1}. With this kind of biasing scheme, the RF output can be made to increase monotonically with RF input. Of course, some penalty is paid in overall efficiency because of the dc power loss in the bias resistor.

V. Oscillators

One of the first applications (1966) of the IMPATT diode was in an oscillator application [39]. The objective was to realize an electronically tunable oscillator to replace the reflex klystron in a short-haul FM radio system. The frequency of oscillation was modulated by varying the dc current. It was soon realized that the modulating sensitivity S (MHz/mA) and the FM noise (Δf_{rms}) were both inversely proportional to circuit Q. This led to the definition of a figure of merit $S/\Delta f_{rms}$ which was a property of the IMPATT diode alone.

Later designs included a varactor diode for frequency modulation. This permitted designing for modulation sensitivity independent of the noise performance.

Most IMPATT oscillator applications have been for fixed frequency operation. These are useful for receiver and transmitter local oscillators[2] and for transmitter signal sources using path-length modulation to achieve a phase-shift-keyed (PSK) digital signal. The noise performance of such an oscillator is predicted using (1).

One of the most fundamental oscillator circuits was invented by Harkless [40] and is shown in Fig. 11. The IMPATT diode was connected to one end of a coaxial line. A cavity resonant at the desired frequency of oscillation couples to the line. A broad-band termination at the other end of the line presents a match at all frequencies other than that of the resonant cavity. Thus the diode sees a high impedance at all other frequencies. The cavity is located so as to present a low impedance to the diode at the operating frequency.

[2]Gunn devices have been more widely used for local oscillator applications below 20 GHz because of their lower noise.

TABLE I
Multiple Diode Oscillators

Frequency GHz	Power Watts	Number of Diodes	Diode Type	Combining Scheme	Source
9.1	10.5	12	Si	Cavity	[44]
5.0	60.0	6	Mod. Read	Cavity	[45]
8.5	22.5	6	Mod. Read	Series	[46]

Many waveguide oscillators were built which are modifications of this basic approach [41]. Many use the cavity in the transmission configuration. Others couple the cavity to the diode in the reaction configuration [42].

Most of these designs were prone to subharmonic or parametric oscillations. Subharmonic oscillations have been observed to reduce the available power from an IMPATT diode by as much as 3 dB. These oscillations were often unnoticed since they occurred at frequencies below the waveguide cutoff. More recently, oscillator circuits have been designed which prevent subharmonic and parametric oscillations [34], [43].

Several high-power CW oscillators have been realized by combining the outputs of many diodes. Examples of such results are presented in Table I.

VI. Amplifiers

IMPATT amplifiers have been built with power outputs, gains, and noise performance comparable with those of medium-power traveling-wave tubes. Their high reliability, together with the advantages of low-voltage operation, have made IMPATT amplifiers an attractive alternative for many medium-power transmitter applications (10 W or less).

The fundamental circuit used for most designs was presented in Fig. 6. In some cases, additional isolators are included between high-gain stages to improve stability. IMPATT diodes are used for the final stages because of their high-power capabilities, but Gunn diodes or transistors are often used for the low-power stages, because of their better noise performance.

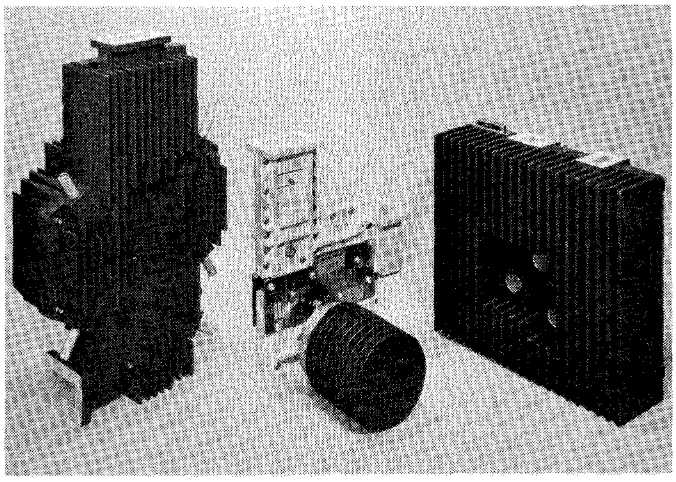

Fig. 12. Three IMPATT amplifiers designed at Bell Laboratories.

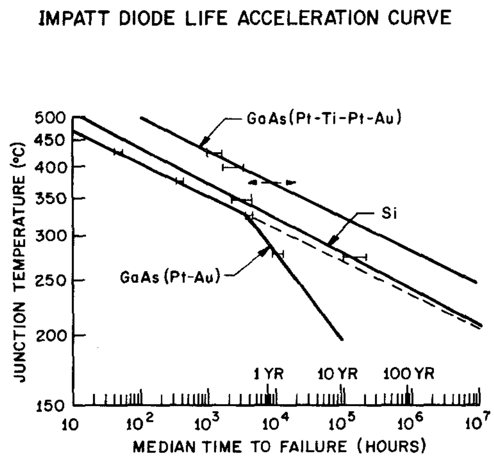

Fig. 13. Life acceleration curves for flat-profile IMPATT diodes.

TABLE II
IMPATT AMPLIFIERS

Frequency GHz	Output Power W.	Gain dB	Noise Figure dB	Overall Efficiency Percent	Stage	Diode Type	Source
6.0	1.0	20	48	4	1	Si (Flat)	[29]
6.0	1.6	22	43	7	1	GaAs (Flat)	[49]
6.0	10	30	30	7	1	GaAs (Flat)	[47]
					2,3	2-GaAs (Flat)	
11.0	3.5	25	36	6	1,2,3	GaAs (Flat)	[48]
6.0	10	40	26	6	1,2,3	Gunn	[50]
					4,5,6	GaAs (Flat)	
					7	Modified-Read	
					8	2-Modified-Read	
13.5	5	57	-	10	1,2,3	GaAs (Flat)	[38]
					4,5,6,7	Modified-Read	

Examples of recent amplifier designs are presented in Table II. Fig. 12 is a photograph of three IMPATT amplifiers developed at Bell Laboratories. The center amplifier is a 1-W 6-GHz amplifier [29], the one on the left is a 10-W 6-GHz amplifier [47], and the one on the right is a 3.5-W 11-GHz amplifier [48].

VII. Reliability

Since IMPATT diodes usually operate at very high temperatures (200°C junction temperature or greater), considerable effort has been expended to maximize the reliability. The first metallization used consisted of a layer of platinum (5000–10 000 Å thick), coated with a layer of gold. The gold was necessary for bonding purposes, and the platinum acted as a barrier to prevent the gold from diffusing into the junction and shorting it out. For GaAs the platinum also formed the Schottky barrier.

For Si p-n junction IMPATT's, this metallization gave excellent reliability, as shown in Fig. 13 [56]. The Si diode failures were dc shorts, caused by gold diffusing through the platinum layer. GaAs Schottky-barrier (flat-profile) diodes with Pt–Au contacts exhibited similar failures at high temperatures. When extrapolated to low temperatures, the predicted life looked satisfactory (dashed line). However, some diodes were giving a decreasing output power with time when being aged at 275°C. Measurements of RF conductance showed a decreasing value with time. A failure criterion was assumed corresponding to a 3-dB decrease in output power. This gave the failure data plotted for 275°C. A line through these data and those for 325°C indicated a second failure mode with much shorter life. Analysis revealed that this failure mode was due to a dc-aided reaction between the Pt and the GaAs [52]. Doping compensation was causing a change in the RF properties of the device. This effect is related to the "platinum chew-in" effect previously recognized as an important degradation mechanism in modified Read diodes.

The diode design was modified to include a Ti barrier between the thin Pt Schottky-barrier contact and the thicker Pt barrier to Au diffusion. The life acceleration curve for this metallization is shown in Fig. 13. The expected life is comparable to, or even better than, that for the Si IMPATT's.

Platinum chew-in is a serious problem with modified Read diodes, where the exact distribution of the doping near the contact is crucial to good RF performance. Various metals have been tried as a Pt to GaAs barrier, including Ti and W. However, a most effective approach has been the use of a p-n junction instead of a Schottky barrier. Median-time-to-failure is predicted to be greater than 10^7 h for 200°C junction temperature [53].

VIII. Conclusions

IMPATT devices have demonstrated their capabilities for solid-state microwave power applications. They have come of age, moving from the laboratory into communications and military applications. High-power GaAs FET's are now becoming available with comparable power capability below 10 GHz. These will be taking over many of the applications previously reserved to IMPATT's. However, above 20 GHz it is expected that the

IMPATT will continue to be the highest power solid-state device available for the foreseeable future.

Acknowledgment

Many of the author's associates have contributed to the understanding of the interactions between IMPATT diodes and their circuits. In particular, he wishes to acknowledge the contributions of C. B. Swan, J. G. Josenhaus, C. A. Brackett, J. E. Morris, H. N. Carlson, I. Tatsuguchi, N. R. Dietrich, W. E. Schroeder and K. Kurokawa. He also wishes to thank J. A. Rupp for the use of his unpublished reliability data.

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High-Frequency Limitations of IMPATT, MITATT, and TUNNETT Mode Devices

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Invited Paper

***Abstract*—High-frequency limitations of IMPATT and other mode devices are explored by concentrating on the details of the large-signal injected current pulse formation. Simple waveform models are given for injected current pulses of large widths, and various scaling relations are also included. The large-signal injected current pulse is calculated by use of a modified Read equation where attention is given to the effect of the intrinsic response time and the tunneling current. The poor high-frequency performance of GaAs devices is explained by postulating that the intrinsic response time is larger than expected. Tunneling current is shown to increase the high-frequency performance of GaAs diodes. Device efficiencies are calculated for specific diode structures by using a computer simulation which includes mixed avalanche-tunnel breakdown. The results for GaAs and Si devices are given, and the results are discussed and compared.**

I. Introduction

MANY REASONS have been given for the high-frequency limitations of IMPATT mode devices such as package effects, series resistance, and skin effects [1] which cause the match between the device and circuit to become increasingly difficult for high-frequency operation. Diffusion-aided spreading of the injected current pulse [2], [3] can also limit the performance of IMPATT mode devices at very high frequencies, and the diffusion can also affect the intrinsic buildup of the injected current pulse [4]. The saturation of the ionization rates at high electric fields [5] will cause a decrease in the device efficiency at high frequencies. Thermal considerations are also important to high-frequency operation of these devices [6]. This paper will concentrate on the details of the injected current pulse formation and show how the pulsewidth is affected by device parameters, material parameters, and frequency. This effect is believed to be the major reason why GaAs IMPATT mode devices have had little experimental success in achieving oscillation in the low millimeter-wave frequency range. GaAs IMPATT mode devices have been built at 50 GHz with good efficiencies [7]. Si mode devices have achieved oscillation in a harmonic mode up to 423 GHz [8] and in a fundamental mode up to 341 GHz [9]. The limit of Si devices to near 400 GHz is probably due to a combination of the previously mentioned effects. The effect of tunneling current on the high-frequency performance is also discussed. Mixed avalanche-tunnel breakdown in semiconductors [10]–[13] and its effect on transit-time devices [14]–[18] has been discussed elsewhere.

The purpose of this paper is to discuss some fundamental high-frequency limitations of IMPATT mode devices where tunneling is also considered. Simple waveform models are given for injected current pulses of large widths, and various scaling relations are also included. The large-signal injected current pulse is calculated by use of a modified Read equation. Device efficiencies are calculated by using a computer simulation which includes mixed tunnel-avalanche breakdown. The results for GaAs and Si devices are given and compared. Three distinct modes of operation are identified for different widths of the generation region. These include the normal IMPATT mode, the MITATT (*mi*xed-*t*unneling-*a*valanche *t*ransit-*t*ime) mode, where both tunneling and avalanche break-

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