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Effect of Domain and Circuit Properties on Oscillations in GaAs

Abstract: A discussion is given of the complications obtaining when a bar of GaAs, generating microwave oscillations, is allowed to interact with an external circuit. Three very different modes of operation can be expected, each corresponding to a mechanism of extinction of the travelling domains of electric field that cause the current modulation. It is seen that the domains may be extinguished (1) when they reach the end of the bar, (2) when the voltage drops too low for the stability of a domain, or (3) when it rises too high. In the last two circumstances, the external circuit plays an important role. Conditions for the existence of the various modes are deduced, and their properties are studied experimentally.

1. Introduction

The generation of microwave power[1] from the current modulation which results from the motion of high electric field domains[2] in GaAs is by now reasonably well understood, at least on a phenomenological basis, for the case where the voltage across the GaAs device is not allowed to vary significantly. The current waveform then consists of a series of spikes, whose period is nearly equal to the transit time of domains. However, when the voltage variation is allowed to become large, in an attempt to extract the maximum microwave power, the situation becomes much more complicated and the frequency sometimes, but not always, departs from the transit-time value. Also, there arise large and unexplained variations in the efficiency of power conversion and in the degree to which the frequency is affected by changes in the external circuit. In this paper, the existence of several distinct modes of operation is proposed. The modes are classified according to the mechanism of domain extinction involved, criteria for their existence are developed, and experimental results are given in support.

2. Classification of modes of oscillation

In the cases considered here, dc power is converted into rf power through the modulation of current which arises when domains of high electric field are nucleated and extinguished in a bar of *n*-type GaAs of roughly uniform resistivity and cross section. From the point of view of the external circuit, it is irrelevant that the domains move down the bar during their lifetime; rather, all that matters is the modulation of current that results. To understand the processes involved in modulation,[2,3] it is necessary to remember that a domain is nucleated (usually at the cathode) when the current through the bar exceeds momentarily some threshold value I_T, after which the resistance of the bar rises to a value determined by the domain characteristic. The voltage V_T required to produce this current in a bar not already containing a domain depends on the length of the bar and on the drop across the region of anomalously high electric field next to the cathode. If a domain already exists, a voltage V_T' much greater than V_T will be required to nucleate a second domain, and only one of the two will survive. On the other hand, a domain may be extinguished, with a corresponding decrease in resistance, in at least three different ways: (1) when it reaches the anode or possibly some other critical point in the bar; (2) if the voltage across the bar falls below a certain minimum value $V_{\min}(<V_T)$ required to support a domain; (3) if a second domain is nucleated in the same bar. Since the modulation of current, and hence the nature of the externally observable oscillations, is determined by the appearance and disappearance of domains, it is convenient to classify the various possible modes of oscillation according to these extinction mechanisms.

2.1 *Transit time modes*

The simplest mode of oscillation, and the first to be observed experimentally, is that in which a domain is nucleated at the cathode and travels to the anode, where it is extinguished. A new domain is then nucleated immediately at the cathode.* The current rises momentarily during the extinction and renucleation process, and its waveform

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* Nucleation and extinction may occur at points other than the real anode and cathode, where suitable electric field gradients occur. This introduces no changes in principle.

consists of a series of pulses whose period is equal to the transit time of a domain, plus a small delay in nucleation. This mode is the only type of oscillation observable when the applied voltage is held constant.

If the current is passed through a resonant external load circuit, then, provided the voltage developed across the circuit is not large enough to interfere with the nucleation-extinction process (that is, V remains between V_T and V_T'), the circuit will act mainly as a frequency selective filter which transfers power at certain frequencies to a resistive load. For purposes of circuit analysis, the bar of GaAs can be described as primarily a current generator, which periodically excites the free oscillations of the resonant circuit. Three possible cases arise, depending on the relationship between the period of these oscillations and of the current.

2.1.1 *Fundamental transit-time mode*

If the periods are similar, and the loaded Q of the circuit is not too low, then the voltage across the circuit will approximate a sine wave of the fundamental transit-time frequency, and only this frequency will appear in significant magnitude at the load. The efficiency will be quite low, as the frequency spectrum of the current contains relatively little energy at the fundamental frequency.

2.1.2 *Harmonic transit-time modes*

When the period of free oscillation of the resonant circuit is near an integral submultiple $1/n$ of that of the current, a voltage will be developed at the n-th harmonic of the transit-time frequency. If only the ac current generation properties of the bar are taken into account, and the Q is again not too low, this voltage will have a waveform consisting of a series of damped sinusoids, reinforced every n cycles by a pulse of current from the bar. While it contains a domain, however, the bar has an internal impedance whose real part may be negative. Thus the damping of the whole system may be less than that of the loaded resonator alone, and the harmonic voltage may remain constant, or even grow, in the period between pulses. The extinction-renucleation process, however, ensures a rigid synchronism between the voltage oscillations and the motion of domains, since the resistance of the bar periodically reverts briefly to a low positive value. Thus the frequency remains controlled by the transit time.

2.1.3 *Non-sinusoidal transit-time modes*

For completeness, the classification should include modes where the dissipation in the resonator, or its mistuning from a multiple of the transit-time frequency, is great enough to allow two or more frequency components to reach the load. This obviously includes the purely resistive case ($Q = 0$).

• 2.2 *Resonant modes*

Entirely different modes of operation result when the extinction of domains is caused, not by their arrival at the anode, but by variations in voltage across the bar resulting from the operation of the external circuit. Under appropriate conditions, the timing of the domain nucleation-extinction process will be determined by the resonant behaviour of the circuit, as loaded by the admittance of the bar, and it will be this that determines the frequency of operation.

Two types of resonant operation may be distinguished. One obtains when it is a *decrease* in voltage that leads to the extinction of a domain. The other (surprisingly, perhaps) obtains when it is an *increase*.

2.2.1 *Under-voltage resonant mode*

When the combination of the steady bias (power-supply) voltage and the rf voltage across the resonator is such that the variations in the latter bring V, alternately *above* V_T and, before the domain formed has reached the anode, *below* $V_{\min}$, then the lifetime of the domain, and the waveform of the resulting current modulation, are determined in a simple way by the voltage waveform. The frequency of oscillation is then fixed by the resonance of the external circuit, as loaded by the admittance of the bar, and may be less or much greater than the transit-time frequency. The requirement that the domain be extinguished before reaching the anode means that the transit time cannot be much less than a half cycle of the resonator voltage. This sets a lower limit on the operating frequency of about half the transit time frequency. Apart from this limitation, the latter plays no role whatever in determining the operating frequency, and the length of the bar is significant only to the extent that it affects its admittance. The motion of the domain is of no consequence to the operation of the circuit until it reaches the anode, which it never has the chance to do. Thus the bar behaves, so far as the external circuit is concerned, as a negative resistance device, and its properties as an autonomous current generator are never called into play.

In this mode of operation, the bar remains in a low-resistance state for the appreciable period between the times when V drops below $V_{\min}$ and when it rises above V_T again. Thus the current waveform more nearly resembles a square wave than in the transit-time modes, and the efficiency should be somewhat higher than in those modes. The control of the frequency by the external circuit means that a wide tuning range should also be possible in this mode.

2.2.2 *Over-voltage resonant mode*

Another mode of operation exists in which a domain is extinguished before it reaches the anode, but in this case it is not because the voltage is too low, but because it is too high for steady domain propagation. This possibility results from the existence of a limiting value V_L of the domain voltage,[3] above which the domain no longer propagates steadily; when this voltage is exceeded, the current begins to rise with time, in a way which becomes increasingly noisy.* When the rising current reaches the threshold value I_T, a new domain will be nucleated at the cathode. This situation, involving two domains in series in the one sample, becomes unstable when the voltage is reduced (because of their voltage-controlled negative resistance characteristics) and one of the domains will be extinguished. Although the details of this process remain obscure, it is found experimentally that the domain which survives is the new one. Thus, in the presence of an rf component, a high average voltage across the bar can give rise to a cyclic process whose period is again determined by the resonance of the external circuit. In this case the process of extinction involves the competition among domains for the available voltage, rather than a simple decrease in voltage below $V_{\min}$.

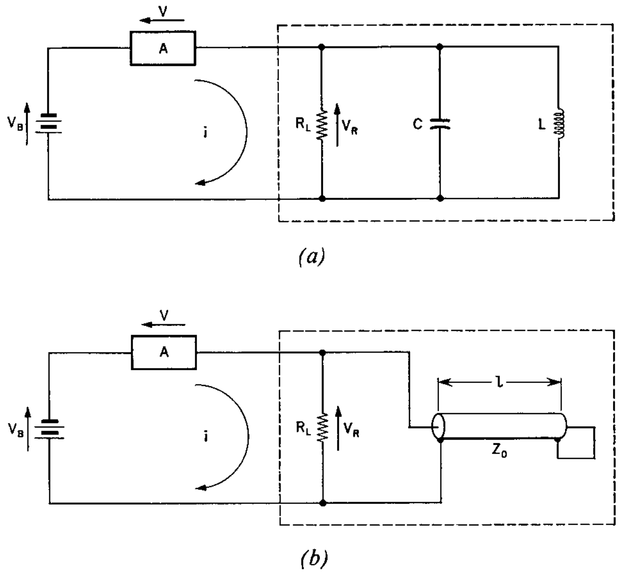
Because of the noisy behaviour of the current at voltages above V_L, this mode of oscillation is likely to be somewhat incoherent, and the efficiency will be low because the rf voltage is only a fraction of the average value.

- 2.3 *Mixed modes*

If the voltage waveform were such that V were greater than $V_{\min}$ but less than V_T when the domain reached the anode, a new domain would not be nucleated until the voltage rose again. In this mixed mode, the current pulses would be slightly wider than in the transit time case, and both the transit time and the period of the external circuit would affect the operation of the circuit. This mode, if it is indeed stable, could exist only over a very limited range of operating conditions. Another mixed mode which can exist in principle is one that might appear if the negative resistance of a long device, due to the domain, were strong enough. Then, during transit-time oscillations at low frequency, growing oscillations in a suitable high-frequency resonator might be built up from a small amplitude during each transit time cycle. We have not observed either of these modes.

3. Effect of circuit conditions on mode of oscillation

The classification scheme adopted above takes account only of the mechanism involved in the various modes of oscillation, and does not consider the circuit conditions necessary for their operation. Such conditions are the subject of the present section.



(a)

(b)

Figure 1 The basic circuits considered. The GaAs device is shown as rectangle A, the resonator is shown within dashed lines: in (*a*)–a lumped-constant resonator; in (*b*)–a transmission line or cavity resonator.

Before going into detail, it is necessary to distinguish between ultimately stable modes which appear immediately when the circuit is switched on, those which appear spontaneously only after the transient appearance of other modes, and those which are accessible only by the external manipulation of circuit variables after switching on. These differences between modes arise in basically the same way in all highly nonlinear oscillating systems.

- 3.1 *Characteristics of the circuit*

To provide a definite basis for discussion, we consider the circuits of Fig. 1 which are identical except for the type of resonator considered (an L-C lumped element in Fig. 1a, a short-circuited transmission line in Fig. 1b). For purposes of analysis, the reactive elements are considered to be lossless; the finite Q of the resonator, resulting both from internal losses and from coupling to an external load, is represented by a single shunt resistor R_L. In analyzing these circuits, two impedance properties of the resonator are important. One of these is the resonant impedance, which determines the steady state voltage that is built up under resonant conditions when the current i flowing through the circuit is sinusoidal; according to our assumptions, this is simply the resistance R_L. The second property is the transient impedance Z, which measures the amplitude of the voltage oscillation at the natural frequency ω_0 of the circuit resulting from a sudden change in the current i. In the absence of any loading, the transient impedance would be simply the dynamic impedance $Z_0 = (L/C)^{1/2}$ for an L-C circuit, or the characteristic impedance Z_0 for a transmission line. When the circuit

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* This effect has been ascribed to the beginning of avalanche ionization in the very high field existing in the domain.[4]

is loaded, a correction is required for the decay in amplitude of the oscillation. In the subsequent analysis, it is the amplitude of the first reversal of voltage (i.e., the second half-cycle) which is important. The height of this particular extremum may be calculated by the use of an effective transient impedance $Z_{0(\mathrm{eff})}$, which is given by

$$Z_{0(\mathrm{eff})} = Z_0/(1 + Z_0/R)^2, \tag{1}$$

for the transmission line case, and by

$$Z_{0(\mathrm{eff})} = Z_0 \exp\left\{-\frac{1}{2Q}\left[\frac{3\pi}{2} - \mathrm{Tan}^{-1}\left(\frac{1}{2Q}\right)\right]\right\} \tag{2}$$

for the L-C circuit. Here Q is the quality factor of the circuit at its natural frequency ω_0 (not its resonant frequency), and is given by

$$Q^2 = (R^2/Z_0^2) - 1/4. \tag{3}$$

The resistance R is to be taken as the parallel combination of R_L with the conductance of the GaAs bar. For the transmission line, the natural frequency ω_0 is simply given by

$$\omega_0 = \pi/2\tau_L, \tag{4}$$

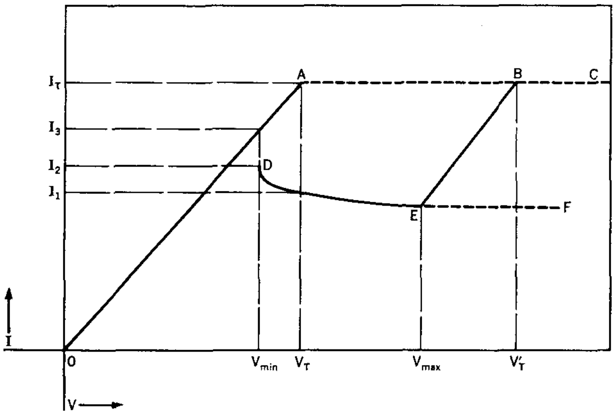
where τ_L is the delay time of the line, whereas for the L-C circuit, it is given by

$$\omega_0^2 = 1/LC - 1/4R^2C^2. \tag{5}$$

• 3.2 *Characteristics of the semiconductor device*

In accordance with the experimental results and discussion given in Ref. 3, and the mechanisms discussed in Section 2, we characterize the behaviour of the bar by means of a time-dependent current-voltage characteristic, as in Fig. 2. Neglecting once again the effects of the anomalous cathode drop of potential, we represent by OA in this figure the ohmic resistance of the bar for values of current and voltage less than the threshold values I_T and V_T. The dotted extension ABC represents an unstable characteristic; as soon as the operating point moves into this region, a domain is nucleated, and the operating point moves on to the section DEF which represents the series combination of the low-voltage resistance of the bar and the negative resistance characteristic of the domain. As long as the operating point remains within the segment DE, the domain propagates steadily. If V exceeds $V_{\max}$, the operating point moves at first along EF, but the steady motion ceases and the current begins to increase somewhat noisily with time until the branch EB is reached. This branch represents the series combination of the low voltage resistance of the bar with the essentially voltage-limited characteristic of the unsteady domain, and therefore has about the same slope as OA. If the operating point finally passes the second threshold voltage V_T', so that I_T is again exceeded, then an additional domain is nucleated at the cathode and further complications (not shown) ensue. Even when the operating point lies on the curve DEB, however, it is stable only for a limited time; the point moves back to the branch OABC when the domain is extinguished on reaching the anode. The subsequent history of the operating point then becomes independent of what has gone previously. This also happens if the voltage falls to $V_{\min}$, and the operating point reaches the lower end D of DE. At this point the negative resistance of the steadily travelling domain becomes too strong and causes its extinction, with the return of the point to OA.

Figure 2 Time-dependent current-voltage characteristic of GaAs device.



• 3.3 *Operation of the circuit*

We consider next what happens when the power supply voltage V_B, in the circuits of Fig. 1, is increased from zero slowly, so that the voltage V_R across the resonator at first remains small. Then when V_B reaches the threshold voltage V_T, a domain is nucleated, and the current drops rapidly from I_T to the value I_1, as is shown in Fig. 2. This sets up an oscillation of V_R, which will have reached its most negative value approximately three-quarters of a cycle later, after a time τ_0 given by

$$\omega_0\tau_0 = 3\pi/2 - \mathrm{Tan}^{-1}(1/2Q). \tag{6}$$

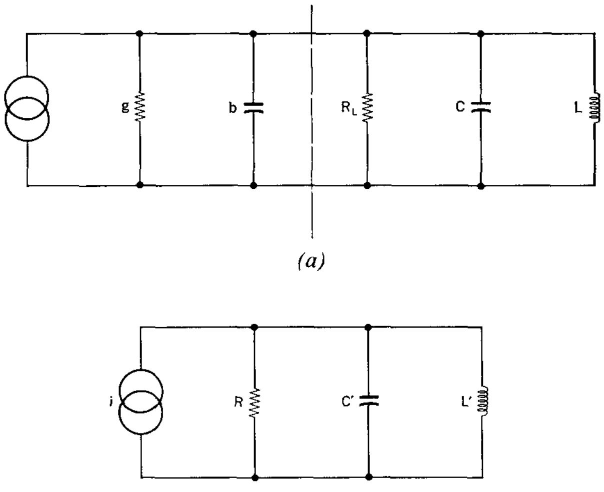
At this instant, V_B will have increased by approximately $\tau_0\, dV_B/dt$. As discussed in Section 3.1, the relevant amplitude of oscillation is equal to $(I_T - I_1)Z_{0(\mathrm{eff})}$, if the time required to nucleate a domain is neglected. If the voltage $V = V_B - V_R$ across the bar drops below $V_{\min}$, the domain will be extinguished, and the current will rise rapidly from I_2 to I_3, as shown in Fig. 2. The criterion for this is given, with sufficient accuracy, by the condition

$$V_T + \tau_0\, dV_B/dt < V_{\min} + (I_T - I_1)Z_{0(\mathrm{eff})}. \tag{7}$$

Once the domain has been extinguished, the operating point will move down OA in Fig. 2 and back again until V_T is reached, whereupon a new domain will be nucleated and the current will change once more from I_T to I_1. Both the change from I_2 to I_3 and that from I_T to I_1 occur in the correct phase to add energy to the resonator, so that the resulting increase in amplitude of oscillation will ordinarily be more than sufficient to extinguish the second domain also. Thus the under-voltage resonant mode will have been established. Since further growth of the amplitude of oscillation can only establish this mode more firmly, the mode will persist if the increase in V_B is halted at some value not too far above V_T. At high values of V_B, the mode may be suppressed again, either because the alternating current delivered by the device cannot sustain the necessary voltage swing $V_B - V_{\min}$ across the resonator, or because the mode becomes unstable with respect to small changes in amplitude. Even if this suppression does not occur, a second domain will be nucleated, with ensuing complications, if V exceeds V_T'; this will happen if V_B exceeds $(V_{\min} + V_T')/2$. Analysis of these effects is bound up with the question of the equilibrium amplitude and conversion efficiency of the mode and is tedious, although straightforward in principle. Beyond pointing out that the relevant circuit parameter in these matters is R_L, rather than Z_0, we shall not discuss them further in this paper.

If condition (7) is not met, so that V does not fall below $V_{\min}$ at the first minimum, then the voltage at subsequent minima will be even higher, and the under-voltage resonant mode will not be established. Instead, the domain will continue until it reaches the anode, and one of the transit-time modes will be set up. The alternating current which gives rise to the subsequent excitation of this mode consists of two components. As the first, there are the impulses of current, delivered at fixed intervals of time, which result from the extinction-renucleation process. As the second, there is the current which flows through the domain during its lifetime as a result of its finite admittance. If the susceptance of the domain can be neglected, then this admittance is simply the conductance corresponding to the appropriately averaged slope of the branch DE of the I-V characteristic in Fig. 2. However, it has been shown[3] that the domain exhibits reactive effects, in that changes in current lag slightly the changes in domain voltage that cause them. These reactive effects, combined with the fact that the domain is effectively in series with the low-voltage resistance of the bar, cause the conductance of the combination to become zero or positive at sufficiently high frequencies. In the absence of quantitative information, we shall simply assign a value $y = g + jb$ to the ac admittance of the specimen, A.

If the duration τ_i of the current impulses is short compared with their spacing τ_t, the transit-time modes in an L-C circuit can be analyzed in terms of the equivalent circuits of Fig. 3. Here we have represented the GaAs device by a parallel combination of a pulse current generator i, an ac conductance g, and a susceptance b; the external circuit is represented by R_L, C, and L, as before.* For frequencies near resonance, this circuit can be simplified to a parallel combination of i, $R = (g + R_L^{-1})^{-1}$, L', and C'. Both L' and C' may be different from L and C if the susceptance b, which has been absorbed by them, depends in a complicated way on frequency. The behaviour of the circuit can then be calculated in a straightforward way as the excitation of $RL'C'$ by i. The result is that the voltage V_ω developed at the resonant frequency ω (which we assume to be the transit-time frequency $2\pi/\tau_t$, or one of its harmonics) is given by



(a)

(b)

Figure 3 (*a*) The ac elements of the circuit, showing equivalent conductance *g*, susceptance *b*, and current source *i* of GaAs device connected to a resonator; (*b*) equivalent circuit of (*a*).

$$V_\omega = i_\omega R. \tag{8}$$

Here i_ω is the component of i at the frequency ω; it is given by

$$i_\omega = \frac{2}{\tau_t} \operatorname{Re} \int_0^{\tau_t} i(t) \exp(-j\omega t)\, dt. \tag{9}$$

If the pulses of current delivered by i are assumed to be rectangular and to have height δI and duration τ_i, this becomes

$$i_\omega = 2\delta I \frac{\tau_i}{\tau_t} \left(\frac{\sin \omega\tau_i}{\omega\tau_i}\right). \tag{10}$$

The value of δI is just the separation between the branches

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* The discussion is given in terms of the L-C version of the circuit, but, with slight alterations, applies equally to the transmission-line version.

AB and DE in Fig. 2, at the value of V existing during the extinction-renucleation process.

The stability of the transit time mode depends on the achievement of a steady state in which the voltage swing across the resonator does not exceed certain limits. This is possible only if the effective resistance R is positive; if it is negative, no steady state is possible. It should be noted that the quantity V_ω represents the voltage amplitude developed at the frequency ω; it does not give directly the greatest positive or negative excursion of the resonator voltage. The steady-state harmonic signal consists of trains of damped sine waves, of frequency ω_0, repeated at intervals of τ_t. Within each period of τ_t, the envelope of the train decays as $\exp(-t/2CR)$. Thus the ratio of the maximum value of the envelope to the mean value is equal to $\theta/[1 - \exp(-\theta)]$, where θ is equal to $\tau_t/2CR$. When the damping is not too great, the magnitudes of the greatest positive and negative excursions may both be taken as equal to the maximum value $|V_R|_{\max}$ of the envelope. Under these conditions, the steady-state mean value of the envelope is approximately V_ω, and so we have

$$|V_R|_{\max} = V_\omega \theta/[1 - \exp(-\theta)]. \tag{11}$$

Thus, a sufficient condition for the persistence of the transit time mode is

$$V_{\max} - V_B > |V_R|_{\max} < V_B - V_T. \tag{12a}$$

If this condition is met, there is no possibility that the domain behaviour will be affected significantly by the variations of V. A necessary condition, however, is

$$V'_T - V_B > |V_R|_{\max} < V_B - V_{\min}, \tag{12b}$$

for if the right-hand condition is not met, the extinction of the domain will be controlled by V, and a transition to the under-voltage resonant mode will occur. Violation of the left-hand condition will lead to the excitation of the over-voltage mode. If we make use of the fact that τ_t is supposed to be n times the resonant period $2\pi(LC)^{\frac{1}{2}}$, and express θ in terms of the resonant Q of the circuit, and define $Z_0 = (L/C)^{\frac{1}{2}}$, then Eqs. (8), (11) and (12a) give the condition

$$V_{\max} - V_B > n\pi i_\omega Z_0/[1 - \exp(n/2Q)] < V_B - V_T. \tag{13}$$

If this relation among the circuit constants is satisfied, the transit-time mode is stable with respect to the mixed, under-voltage, or over-voltage resonant modes.

In the case where the resonator is a transmission line, the analysis is basically the same but, because of the possibility of simultaneous resonance at several harmonics of the transit time frequency, account must be taken of the possibility of a nonsinusoidal waveform. The general case, where the domain susceptance is important, is very complicated. If the susceptance is negligible and the width τ_i of the current pulses is assumed to be less than $2\tau_L$, then the voltage waveform consists of an alternating series of separate pulses that reproduce the shape of the current pulse. At each reflection from the open end the amplitude changes by $(R - Z_0)/(R + Z_0)$, and at every n cycles the pulse train is reinforced by a pulse of current δI. The resulting peak amplitude is given by

$$|V_R|_{\max} = \delta I Z_0 \left(\frac{R}{R + Z_0}\right) \Big/ \left[1 - \left(\frac{R - Z_0}{R + Z_0}\right)^{2n}\right]. \tag{14}$$

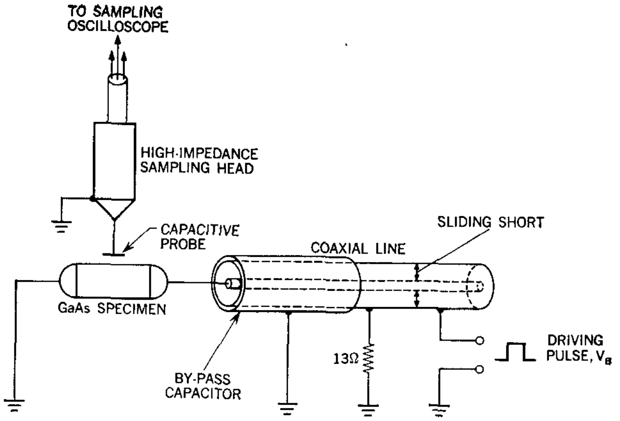
This value may be substituted in Conditions (12a–b). On the other hand, when the effect of the susceptance is large, the relationship between the various resonances of the transmission line will be nonharmonic, and usually only one resonance will coincide with a component of i. Then the analysis may be carried through in terms of this frequency component alone, with results like those for the L-C circuit.

4. Experiment

• 4.1 *Experimental method*

The various modes of oscillation were studied experimentally by observing potential distributions in the GaAs, using techniques of Ref. 3. The only change was that the purely resistive circuit described there was replaced by a resonant one, as shown in Fig. 4. Most of the work was done with the coaxial line shown. The resonant frequency could then be altered by moving the sliding short-circuit, without greatly affecting the circuit impedance $Z_{0(\mathrm{eff})}$. The latter quantity was changed when necessary by altering the diameter of the inner conductor, while holding the inside diameter of the outer conductor constant at 9 mm. A few experiments were made with a lumped L circuit, in which the inner conductor of the coaxial line

Figure 4 The experimental arrangement of Section 4.1.



was replaced by a small coil about 1 cm long. In all cases, the impedance of the pulse driving source was kept low by shunting the outer conductor to ground with a 13 Ω resistor. In parallel with this was the capacitance of about 88 pF of the insulation between the outer conductor and a surrounding grounded block (not shown). The driving pulse was approximately rectangular, of 10–40 nsec duration, and was obtained by discharging a length of coaxial transmission line through a coaxially mounted mercury wetted-contact relay. Various minor distortions of the pulse were corrected by the use of C-R circuits between the pulse generator and the oscillator.

No attempt was made in this preliminary work to extract useful rf power from the circuit, to measure current waveforms, or to make quantitative comparisons with theory. Instead, attention was concentrated on demonstrating qualitatively the differences between modes and the circuit conditions that are necessary for their appearance. Even this proved impossible if measurements were restricted to the voltage across the specimen, and so more detailed observations were necessary. A quick check of the basic domain period involved could be obtained from measurements on the potential at a point near the cathode contact (which was normally grounded), since this potential was closely correlated with the nucleation of domains. Further information was obtained by following the history of one or two domains as they travelled through the sample by photographing a display of potential versus distance at successive instants.[3] In dealing with the higher frequencies the resolution of the technique (0.5 nsec, 20 microns) was barely adequate, but the various qualitative features could be observed.

The GaAs specimens used were similar to those used previously[3], being about 300 microns long and having a resistivity of about 0.7Ω cm and a mobility of 5500 cm^2 V^{-1} sec^{-1}. The low-voltage resistances were in the range 20–130Ω.

- 4.2 *Results*

In general, all modes of oscillation could be elicited from each specimen by a suitable choice of circuit conditions. For a given specimen, it was verified that there was a lower limit for Z_0, below which only transit-time and over-voltage modes could be observed. On raising Z_0 above this value, the under-voltage resonant mode became progressively easier to elicit, as expected theoretically. Data were recorded to illustrate the nature of each mode and in one case the effect of circuit tuning on frequency of oscillation was studied systematically.

4.2.1 *Transit-time modes*

Transit-time modes were observed at low values of Z_0, as mentioned above, and at somewhat higher values when either V_B or dV_B/dt was in a range which excluded either of the resonant modes. A typical example is shown in Fig. 5, where the circuit (in this case of lumped-L type) is tuned to the third harmonic of the transit-time frequency. In Fig. 5a is shown the voltage waveform both at the anode and at a point 40 microns away from the cathode, both measured with respect to the cathode. It will be seen

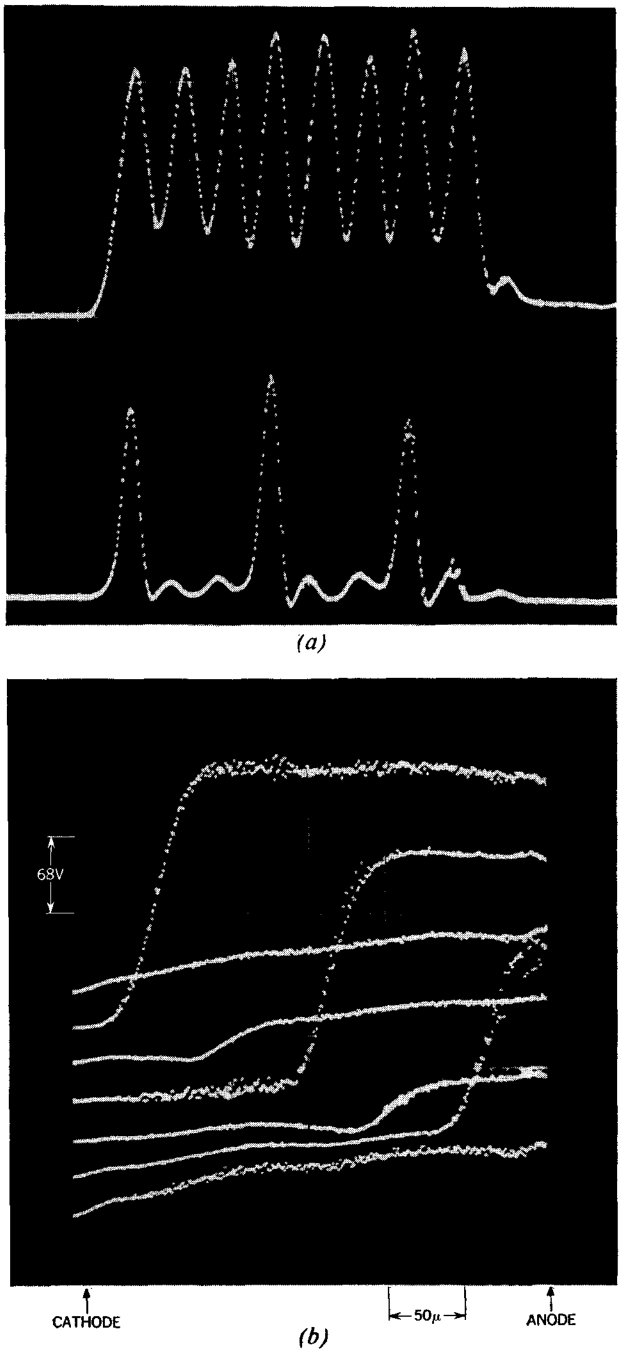


Figure 5 Third-harmonic transit time mode: (*a*) *above*–voltage waveform at anode; *below*–voltage waveform 40 microns from cathode. (*b*) sequence of potential distribution traces.

that, whereas the anode voltage is a nearly pure sine wave of about 830 MHz frequency, the voltage near the cathode rises momentarily to a high value (indicating the nucleation of a domain there) only once every three cycles. In the intervals between the resulting pulses of current, the resonator undergoes almost free oscillations. Close examination of the anode waveform shows that in fact the amplitude *grows* slightly during the passage of the first domain, showing that the ac conductance of the device as a whole is slightly negative during this time, presumably as a result of the negative conductance of the domain. As might be expected, the clean anode waveform shown was obtained only when the resonant frequency of the circuit and the third harmonic of the transit-time frequency were very nearly equal. Increasing the supply voltage V_B was found* to increase the former and to decrease the latter. Thus it was convenient to bring the two into synchronism by adjusting the amplitude of the driving pulse, rather than by varying the physical elements of the circuit. Because the effects act in opposite directions, the range of relative adjustment is surprisingly large; in the present instance, it extended from third-harmonic almost to second-harmonic operation.

In Fig. 5b is shown the progress of the second domain to be nucleated, represented by a sequence of potential distribution curves. Reading downward on the extreme left, the curves show the distribution at successive minima and maxima of the anode voltage. The sequence starts from the minimum immediately preceding the nucleation of the domain, and continues to the corresponding time in the history of the next domain. Thus Fig. 5b spans just over one complete transit time cycle, but spans three cycles of anode voltage. The domain is nucleated near the cathode (shown by the arrow) at some time in the intervals between the first and second curves. It will be seen that, even though the voltage across the domain falls to a low value at each minimum of anode voltage, it is extinguished only when it reaches the anode (the last curve). When this happens, a new domain is nucleated and the process repeats.

4.2.2 *Under-voltage resonant mode*

With an external circuit modified† so as to increase the transient impedance $Z_{0(\mathrm{eff})}$, the amplitude of the voltage oscillations described in the last section became large enough to extinguish the first domain before its arrival at the anode, and the under-voltage resonant mode appeared in persistent form. The resulting anode voltage waveform is shown in Fig. 6a; the bright spots at 0.2 nsec intervals indicate the times at which the corresponding potential distribution curves shown in Fig. 6b were measured. In order to avoid the confusion of too many overlapping traces, the latter are not positioned strictly according to their time sequence; the sequence is shown by the numbers to the right. From Fig. 6b, it will be seen that the domain is extinguished by the time it reaches about the center of the specimen (trace 11), as a result of the voltage across it dropping to zero. When the anode voltage rises again, a new domain is nucleated at the cathode.

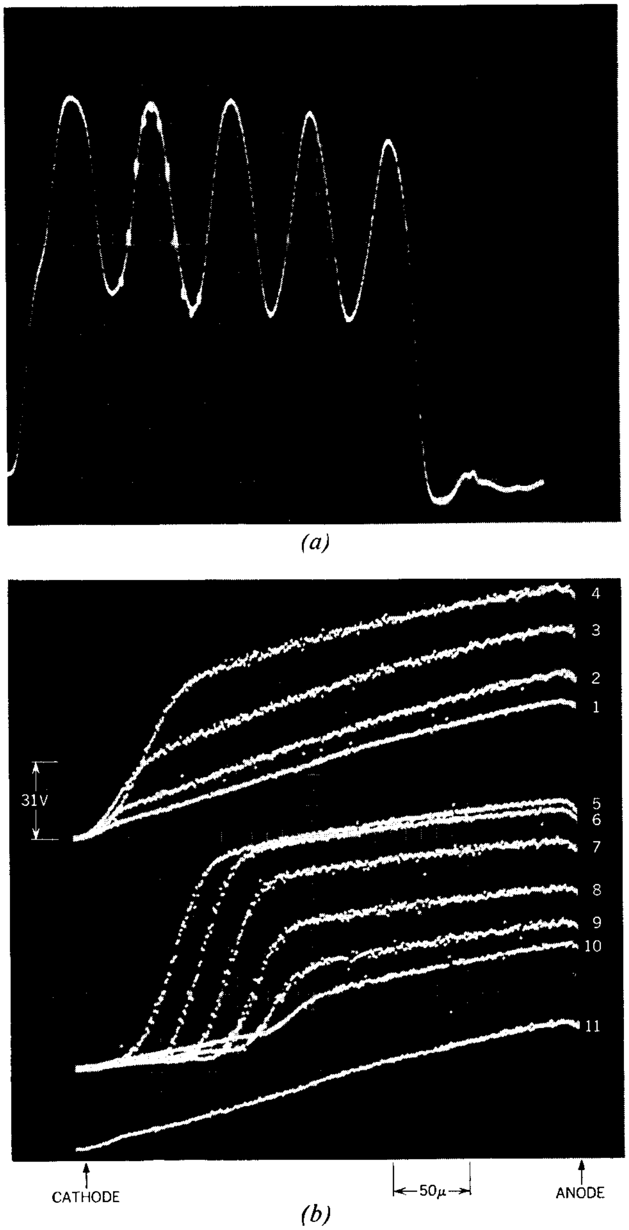


Figure 6 Under-voltage resonant mode: (*a*) voltage waveform at anode; (*b*) sequence of potential distribution traces.

By using a GaAs bar of larger cross section, and hence of increased threshold current, it was found possible to

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* The reasons for these effects are that both the velocity and the positive susceptance of the domain decrease when the voltage across it increases.[3]

† This modification also reduced the natural frequency ω_0 slightly.

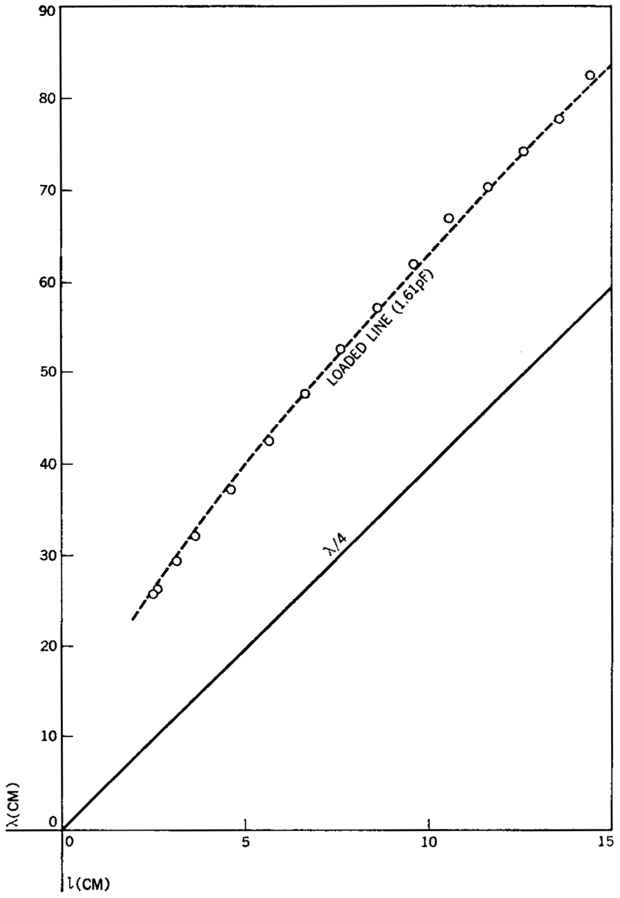
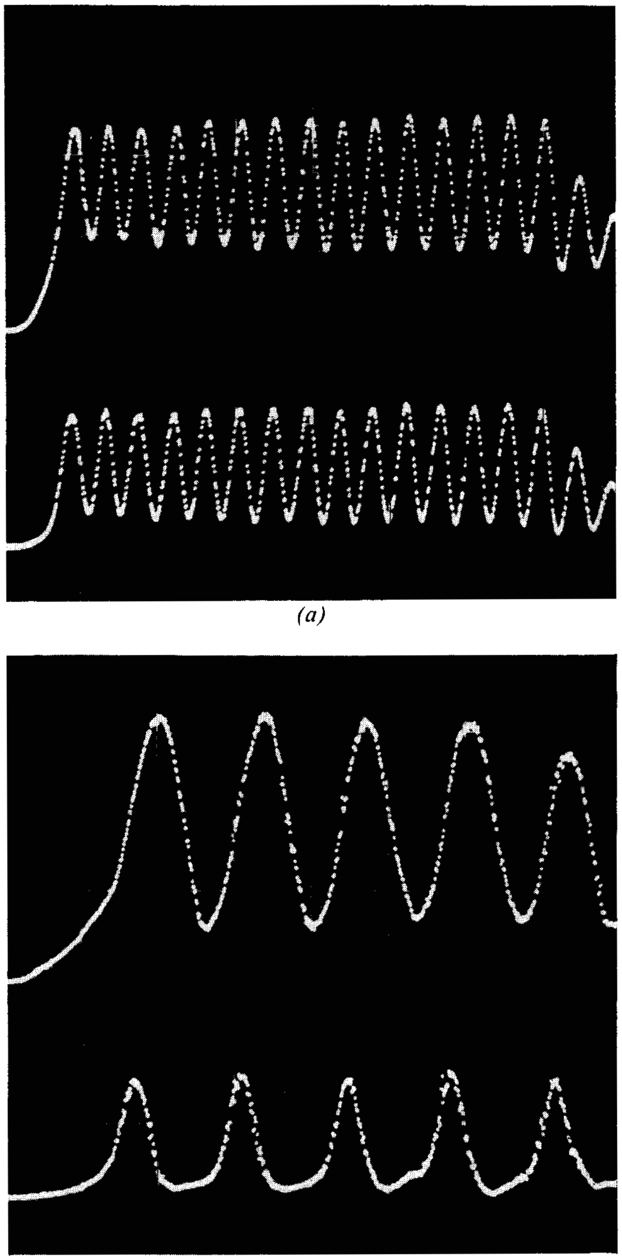


Figure 7 Tuning curve for under-voltage resonant mode.

elicit the under-voltage resonant mode using a variable length of air-spaced coaxial line as the resonator. The effects of changes in ω_0 and $Z_{0\,(\mathrm{eff})}$ could then be separated. When the characteristic impedance of the line was 105Ω, the mode appeared after a delay of about 3 nsec, during which one (fundamental) cycle of a harmonic transit-time mode was executed. This delay was eliminated when the impedance was raised to 130Ω; under these conditions, the relationship between line length and frequency of oscillation was explored. It was found that there was a lower limit of length, below which the transit time mode reappeared. This is believed to have been due to the reduction in $Z_{0\,(\mathrm{eff})}$ resulting from the loading of the line by the electronic admittance of the bar; this effect should be progressively more pronounced with decreasing line length. The limit on line length could be reduced somewhat, and thus the maximum frequency of the resonant mode increased, by slightly modifying the shape of the applied pulse so as to reduce dV_B/dt, Eq. (7). The measured relationship between line length and wavelength of oscillation is shown by the points in Fig. 7. During this measurement, all other operating conditions remained unchanged. Thus it will be seen that the wavelength could be varied from 25.8 to 82.8 cm (frequency from 362 to 1160 MHz) under the control of a single adjustment. The lower limit of frequency was fixed by mechanical limits on the length of the adjustable line, not by electrical considerations. The nature of this mode was confirmed by comparisons, made


(a)

(b)

Figure 8 Voltage waveforms for under-voltage resonant mode. In each case, anode voltage is uppermost and the lower trace is voltage at point 40 microns from cathode. (*a*) at maximum frequency; (*b*) at minimum frequency.

at both ends of the continuous tuning range, of the anode voltage waveform with that at a point 40 microns from the cathode. The results, shown in Figs. 8a and 8b, demonstrate that in each case a domain is nucleated on every cycle of the anode voltage (cf. Fig. 5a).

Even lower frequencies, down to 178 MHz, were obtained when the adjustable line was replaced by fixed lengths of RG 63*B*/*U* cable ($Z_0 = 125\Omega$). Below this frequency, the resonant mode could not be achieved because the domain reached the anode before the voltage fell below $V_{\min}$. It is believed that if the mechanical difficulties were overcome, continuous tuning between this lowest frequency of 178 MHz and the maximum of 1160 MHz would be possible, representing a range of 6.5:1. For comparison, the transit time frequency of this bar was found, as expected from its length, to be about 300 MHz. Thus it was verified that the under-voltage resonant mode can be used to generate frequencies both greater and less than the transit time frequency.

By comparing the experimental data with the line in Fig. 7 labelled "$\lambda/4$" it will be seen that the length of the line is by no means equal to a quarter wavelength, but is always less. This discrepancy can, however, be accounted for if the line is assumed to be loaded by a constant capacitance of 1.61 pF. Then the calculated relationship between l and λ, shown by the dashed line, fits the experimental points extremely well. It is not known how much of this capacitance is due to circuit strays, and how much to the susceptance (averaged over an rf cycle) of the GaAs device.

4.2.3 *Over-voltage resonant mode*

With most of the GaAs devices, rather noisy oscillations of high frequency appeared when the driving voltage was increased to the neighbourhood of $V_{\max}$ and the resonance of the circuit was adjusted to a suitable value. The nature of these oscillations was investigated, as done before, by making measurements of the potential distribution. In this case, because of the rapid changes of distribution, the measurements were made at intervals of 0.1 nsec. Typical results are shown in Fig. 9. They extend over approximately half a cycle of the oscillation, which had a frequency of about 1.2 GHz. The first trace (at the top) shows the potential distribution at the instant when the anode voltage is a minimum. A domain is present at a point about 100 microns from the cathode. In the next trace, the domain has moved towards the anode, the anode voltage has risen slightly, and the cathode drop is beginning to increase. In the third trace, the anode voltage has risen further, but the domain voltage has *decreased*, and the cathode drop has increased considerably. This process is continued in the last three traces; by the fifth trace (which corresponds in time to a maximum of the anode voltage) a new domain is beginning to separate from the cathode drop. In the last trace, this new domain is fully established, and the old one is almost extinguished. In the time remaining between this trace and the next minimum of voltage, the new domain moves to a position corresponding to the first trace, and the process then repeats.

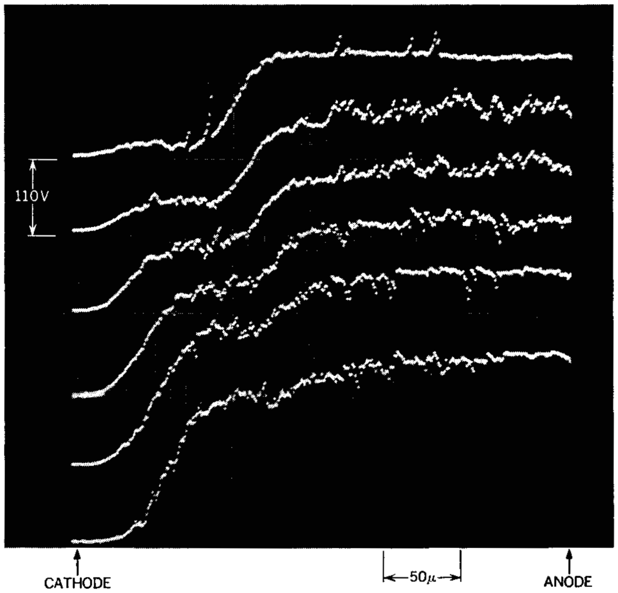


Figure 9 Sequence of potential distribution traces illustrating over-voltage resonant mode.

5. Discussion

Although no attempt was made in the present work to correlate differences in mode of operation with differences in practically important quantities such as oscillator efficiency and tuning range, it appears likely that such correlations exist. In particular, it is suggested that the unexplained large differences in these quantities which have been observed from time to time, are due to unrecognized changes between the transit-time and under-voltage resonant modes of operation. As this paper has pointed out, the dominant factors determining the mode of operation should be, on the one hand, the relations between the current and voltage levels of the device (the "device impedance"*) and, on the other, the dynamic and steady-state impedances of the circuit. Consequently, it should now be possible to choose the device and circuit impedances so as to realize the desired mode of operation.

A transition between the under-voltage resonant mode and the transit-time mode may also be responsible for the phenomenon of "second threshold" which is sometimes observed. In it, the *average* current supplied by the power supply is observed to drop when the voltage is raised to

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* This should not be confused with the low-voltage resistance of the device, which is usually an irrelevant parameter.

the threshold value for oscillation, and to drop again when some higher critical voltage is exceeded. The second threshold is usually accompanied by a drastic change in frequency. It is suggested that between the first and second thresholds, resonant oscillations are excited, but that at the second threshold a change to the transit time mode occurs; other things remaining constant, this will be a natural result of increasing V_B. Because of the difference in current waveforms, the transit-time mode has a lower value of average current.

The existence of a large positive susceptance in the admittance presented by the oscillating GaAs device to the resonator has been recognized since the earliest experiments[1] on rf power generation and it has been confirmed in subsequent experiments.[5] However, its origin has continued to be uncertain. Such a positive susceptance could arise in three ways. It could result from the stray capacitance of the device leads and package, or from the susceptance of the free domain itself,[3] or from a phase shift due to the delays involved in domain nucleation and extinction. It is not likely to be caused by the geometrical capacitance of the bar of GaAs because, as in the cases considered here, the operating frequency is much less than the low-field dielectric relaxation frequency. The stray capacitance will, and the domain susceptance may, contribute a susceptance proportional to frequency (constant capacitance). The phase shift due to nucleation and extinction, on the other hand, can be represented as the result of a roughly constant time lag (nucleation plus extinction times), added to a constant phase shift due to the hysteresis between domain extinction and nucleation. The last, which exists only in the under-voltage resonant mode, results from the difference between V_T and $V_{\min}$, and will give rise to a susceptance independent of frequency. Since the data of Fig. 7 indicate a constant capacitance, the contribution of the hysteresis would seem to be negligible; it is not yet possible to distinguish between the contributions of stray capacitance, domain susceptance, and nucleation-extinction delays.

The over-voltage resonant mode of oscillation always appears to be somewhat incoherent, no doubt as a result of the periodic movement of the operating points into the unsteady region of the domain characteristic. Despite the use of full smoothing on the sampling oscilloscope, the measurements shown in Fig. 9 reflect this lack of coherence by their noisy appearance.

The characteristic feature of the over-voltage resonant mode—the extinction of the domain by a high voltage—is clearly demonstrated in Fig. 9, but the details of the process seem a little more complicated than the discussion of Section 2.2.2 would suggest. In the first place, the oscillations seem to be observable only over an unexpectedly narrow range of resonator adjustment, as long as the supply voltage V_T is kept constant. Secondly, Figure 9 shows that the new domain is nucleated while the device voltage V is rising, rather than when it reaches its maximum value. Both these results suggest that phase shifts, possibly those associated with domain nucleation and with domain susceptance, play an even more important part in this mode of oscillation.

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