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THE OPTIMUM WIDTH FOR LHL-GaAs-IMPATT DIODES

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ABSTRACT

In this paper the results of an extensive study of the effects of the drift region width on the performance of LHL-GaAs-IMPATT diodes are presented. These results have been obtained using an IMPATT-diode full scale computer simulation program. It is demonstrated that the transition between the regular IMPATT mode and the high-efficiency modes becomes more abrupt as the drift region width is increased. It is also found that when the diode operates according to the high-efficiency modes the efficiency is not a sensitive function of the drift region width. The anomalous behaviour of the admittance of the diode is found to be caused by the increase of the component of the total current contributing to the power generation mechanism at the expenense of the cold-capacitive current. It is demonstrated that for the diodes whose drift region width is optimized for the regular IMPATT mode the efficiency remains always high and the hysterises in the tuning characteristics are less significant

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I. INTRODUCTION

The LHL-GaAs-IMPATT diode is the most powerful and efficient solid-state source of microwave CW-power at the X-band frequency range [1-4]. It has many wide applications in communication and airborne radar systems [4]. However, the optimization of such a device is a very difficult and expensive task due to the complexity of the semiconductor transport equations which govern its operation and to the severe nonliearities inherent in these equations. The matter is complicated further by the relatively large number of structural parameters which have to be optimized simultaneously. In this paper, the results of an extensive study of the effects of the drift-region width (X_d) on the performance of LHL-GaAs-IMPATT diode will be presented. These results have been obtained using the IMPATT-diode large-signal full-scale computer-simulation program described elsewhere [5]. This program incorporates the GaAs-material parameters in an exact manner. The diode is assumed to be driven by a terminal voltage V_t whose dc component is V_{dc}. Its ac component is a sinusoidal voltage of amplitude V_{RF} and frequency F. The material parameters employed are those given in reference [6].

It is demonstrated elsewhere [7] that the avalanche region width has no significant effect on the performance. Therefore, the results presented here are for diodes of constant avalanche-region width. All these diodes are n-type doped. They are termed D1, D2,D3 and D4. They have the same structural parameters except that X_d is 3.4, 3.7, 4, and 4.3 μm for them respectively. The other structural parameters are : the avalanche-region width is 0.5 μm, the avalanche-region doping density is 0.5×10^{15} cm^{-3}, the size of the doping clump is 1.7×10^{12} $C.cm^{-3}$ and the drift-region doping density is 3×10^{15} cm^{-3}.

II. THE RESULTS

Fig.1 shows the efficiency as a function of the RF voltage level at three different frequencies for the diodes D1,D2,D3, and D4. Fig.2 shows the conductance and the susceptance of the diodes D3 and D4 respectively as functions of V_{RF}. It is seen that the efficiency increases relatively slowly at the first, then it increases sharply to its maximum value after which it decreases also sharply. It was demonstrated elsewhere [8] that in the first part the diode operates according to the regular-IMPATT mode. The sharp increase of efficiency indicates the onset of the second mode which is a high-efficiency one [8]. At the point of maximum efficiency and just after it, the diode operates according to the third mode which is also a high-efficiency one. Finally,the diode operates according to the fourth mode which is a lossy one [8]. It is also seen that the optimum RF-voltage increases with increasing X_d. This is attributed to the increase of the breakdown voltage V_{dc} which results from increasing X_d . It is also seen that the values of the efficiency when the diodes operate according to the regular-IMPATT mode decrease with increasing X_d while the peak efficiency is only slightly affected by this increase. Consequently, the transition between the regular-IMPATT mode and the high-efficiency modes becomes sharper as X_d is increased. This can be explained as follows :

When the diodes operate according to the regular-IMPATT modes, the motion of electrons in the drift region (DR) is not greatly affected by the negative-differential-mobility region (NDMR) of the velocity-field characteristic of n-GaAs material. Therefore, the velocities of these electrons remain close to the saturation velocity v_s and the transit time is given by X_d divided by v_s. There is an optimum operating frequency associated with this transit time. Equivalently, there is an optimum-drift region width for a given frequency. For the range of frequencies investigated here, X_d of the diode D1 is closer to the optimum value than the other diodes . Consequently, the performance of D1 is better when the diodes operate according to the regular-IMPATT mode. The insensitivity of the maximum efficiency to the increase of X_d will become clear after considering the operation of the diode D3 according to the high-efficiency modes in the following section.

III. THE OPERATION OF THE DIODE D3 ACCORDING TO THE HIGH-EFFICIENCY MODES

Fig.3 shows the induced current density J_i and the spatial distribution of the electron-current density J_n at the following operating conditions : the dc-bias current J_{dc} = 1000 A/cm^2, the operating frequency F = 9 GHz, and the RF-voltage level = 57 V. It is clear that the diode operates according to the second mode of operation of GaAs-IMPATT diodes [8] which is explained as follows :
The avalanche-generated pulse (AGP) afer being injected into the DR moves at almost the saturation velocity v_s for $180° \leq \theta \leq 270°$ where θ is the phase angle in degrees. This AGP is slightly dispersed by the effect of diffusion. As V_t decreases, a small undepleted region is formed besides the ohmic contact. The electrons in this region move into the diode inducing a current which offsets that induced by the AGP. Consequently, J_i decreases and undergoes a dip at $\theta \cong 240°$. after this phase angle,the electric field in the region occupied by the AGP falls in the NDMR. Consequently, the AGP will be bunched and accelerated [9] .Correspondingly, the induced current will increase and have a peak at $\theta = 261°$. Then, the bunching and acceleration of the AGP continue but the electric field behind the AGP becomes smaller than the threshold field necessary to maintain the peak velocity v_p. Therefore, some electrons in the middle of the DR will be almost trapped and J_i decreases. This decrease is not significant because the electrons in the undepleted region (UDR) are now moving towards the ohmic contact inducing a current in phase with that induced by the AGP. The induced current has another peak at $\theta = 279°$. This is attributed to the additional bunching of the AGP and to the increase of the velocity of electrons behind this pulse (which is caused by the increase of the field). For phase angles greater than 279°, J_i decreases due to the extraction of the electrons at the ohmic contact. During the extraction process, the AGP will be dispersed because of the increase of the electric field.

Fig.4 shows the results of simulation when V_{RF} is increased to 58 V. It is seen that the slight increase of V_{RF} has radical effects on the behaviour of the electrons and the waveform of the induced current. The diode is now operating according to the third mode of operation of GaAs-IMPATT diodes [8] which is also termed the premature-collection mode.

This mode is also a high-efficiency one. Its essential feature is that the AGP after being bunched and accelerated as in the previous case, will be collected prematurely by the UDR. The premature collection occurs because the depletion width modulation effect becomes more pronounced for this case. However, the induced current remains always very high during the last quarter of the negative-half cycle because of the high velocity of carriers.

Fig.5 shows the results of simulation when V_{RF} becomes equal to 60 V. In this case the diode operates also according to the premature collection mode. Since the depletion width modulation effect becomes more pronounced than for the previous case, the premature collection occurs earlier. This causes J_i to undergo a large dip at $\theta = 270°$. As the terminal voltage increases, the electrons in the AGP and those injected in the diode during the expansion of the UDR continue to move towards the ohmic contact where they are extracted at velocities close to the peak velocity v_p. The induced current will have a maximum when the density of electrons still existing in the DR is very high and their velocities become very close to v_p.

From the previous discussion, it is clear that during the high-efficiency operation, the AGP moves at velocities close to v_p during the last quarter of the RF cycle, i.e, in the portion of the cycle during which the greater portion of the RF power is generated. The operating conditions must be chosen such that the electric field falls in the NDMR in the portion of the diode occupied by the AGP. In this case, the AGP will be accelerated. If the field behind the pulse is kept smaller than that ahead of it , this pulse will be bunched. Since small alterations of the operating conditions around the optimum values can have radical effects on the induced current waveform while the efficiency is only slightly affected, it can be concluded that if X_d is increased above its optimum value, the optimum electric field distribution in the DR can be restored by slightly altering the operating conditions. Consequently, the peak efficiency is shifted to slightly higher frequency when X_d is increased while its magnitude remains almost unaffected. The reduction of frequency slows down the movement of the front edge of the UDR and therefore, increases the possibility of the premature collection of the AGP at the proper time instant.

IV. THE INTERPRETATION OF THE ANOMALOUS BEHAVIOUR OF THE ADMITTANCE OF THE LHL-GaAs-IMPATT DIODES

It is seen from Fig.2 that at the onset of the high-efficiency operation the conductance increases sharply while the susceptance decreases. As long as the diode is operating according to the high-efficiency modes, the conductance continues to increase while the susceptance continues to decrease. This behaviour is considered to be anomalous because it is in contradiction with the behaviour of the admittance of the diode when it operates according to the regular-IMPATT mode. This anomalous behaviour can be explained as follows :

It is already indicated that the depletion width modulation causes a great number of electrons to be injected into the DR during the third quarter of the RF cycle. These electrons move at velocities close to

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the saturation velocity in a direction opposite to that of the AGP. Therefore, they cause J_i to be reduced. During the last quarter, these electrons move in the same direction as that of the AGP and cause J_i to increase. The net effect is an increase of J_i because the velocities of electrons during extraction are higher than those during injection. Therefore, the component of the total current contributing to the RF-power generation increases at the expence of the cold capacitive current In circuit terms , this means that the conductance of the diode increases and the susceptance decreases.

V. CONCLUSIONS

From the previous discussion, it is concluded that if the LHL-GaAs-IMPATT is operating according to the regular-IMPATT mode, its efficiency is a sensitive function of X_d because the electrons move almost at velocities close to v_s during the negative half cycle. If the diode is operating according to the high-efficiency modes, the efficiency is not a sensitive function of X_d. This is because the efficiency depends mainly on the electric field distribution and the behaviour of electrons in the DR. If X_d is increased, the optimum distribution of electric field can be restored by slightly altering the operating conditions. Furthermore, during the last quarter of the RF cycle, the electrons move at velocities close to the peak velocity. Therefore, J_i will remain very high during the portion of the cycle where the maximum amount of RF power is generated. All these effects explain why the increase of the efficiency at the onset of the high-efficiency modes becomes sharper when X_d is increased. The anomalous behaviour of the admittance of the diode during the high-efficiency operation is attributed to the increase of the component of the total current contributing to the power generation mechanism. This anomalous behaviour becomes more pronounced when X_d is increased due to the same reasons leading to the sharper increase of efficiency with increasing X_d.

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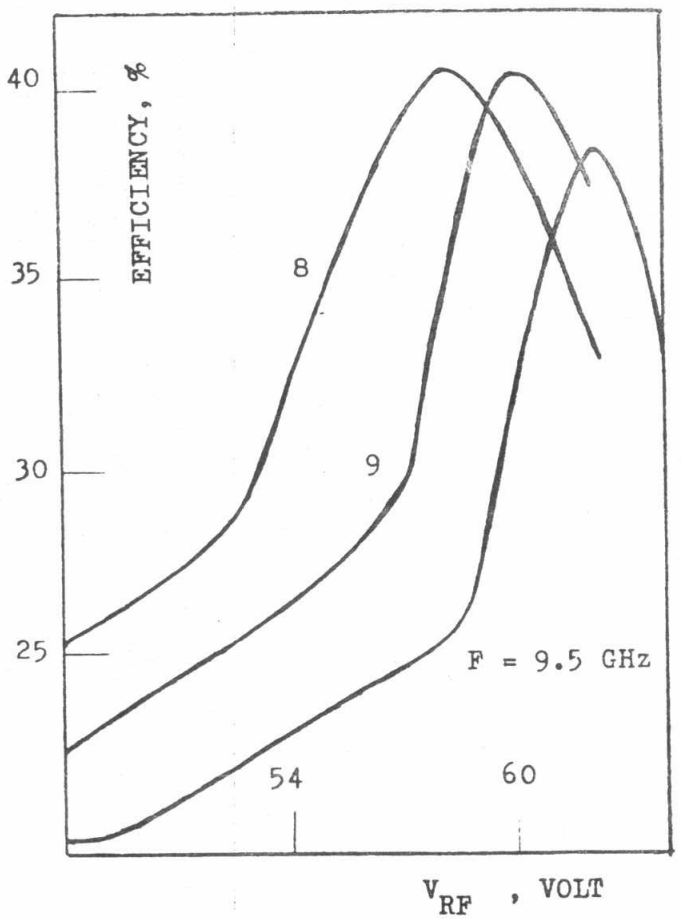

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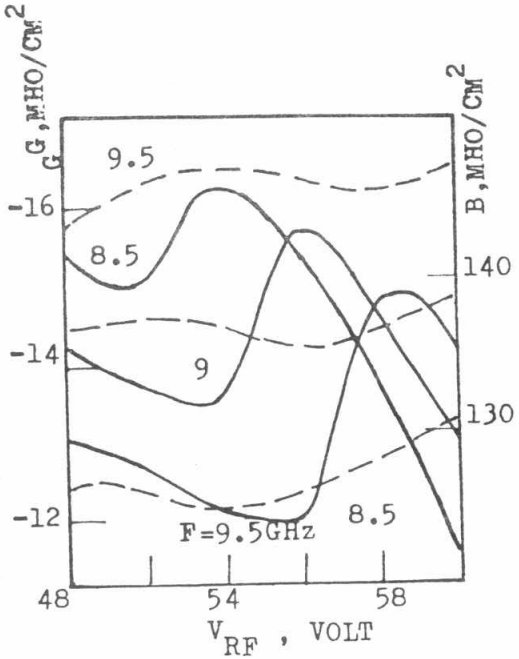
Fig.1 (continued)



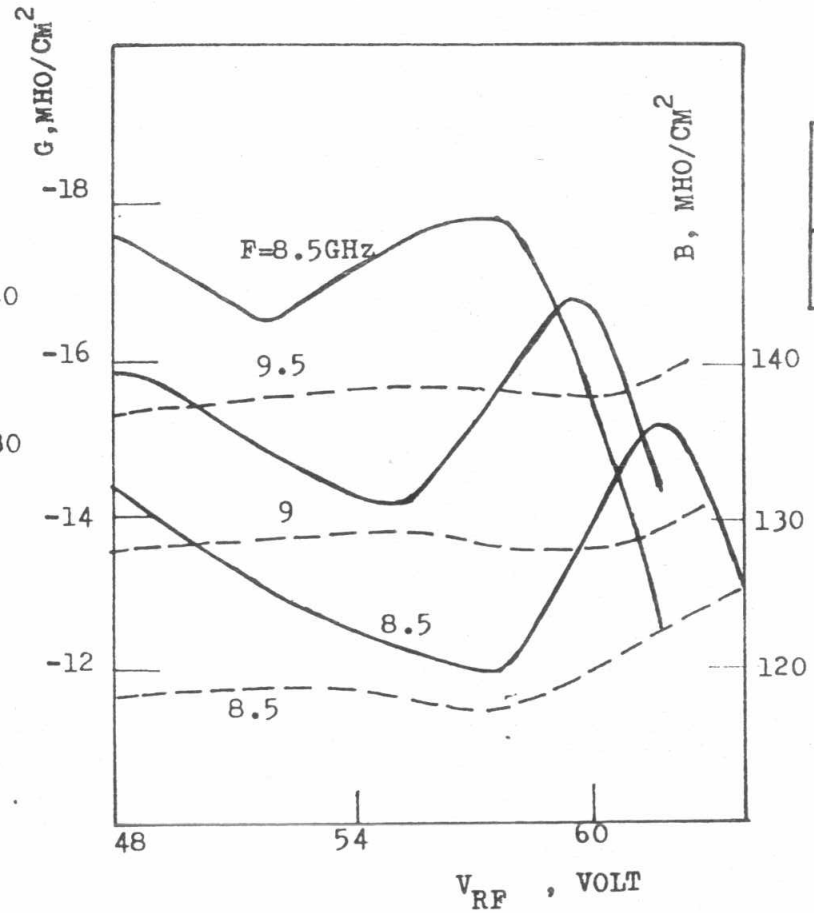


Fig.2 : The conductance G and the susceptance B vs. V_{RF} for the diodes D3 and D4 respectively.

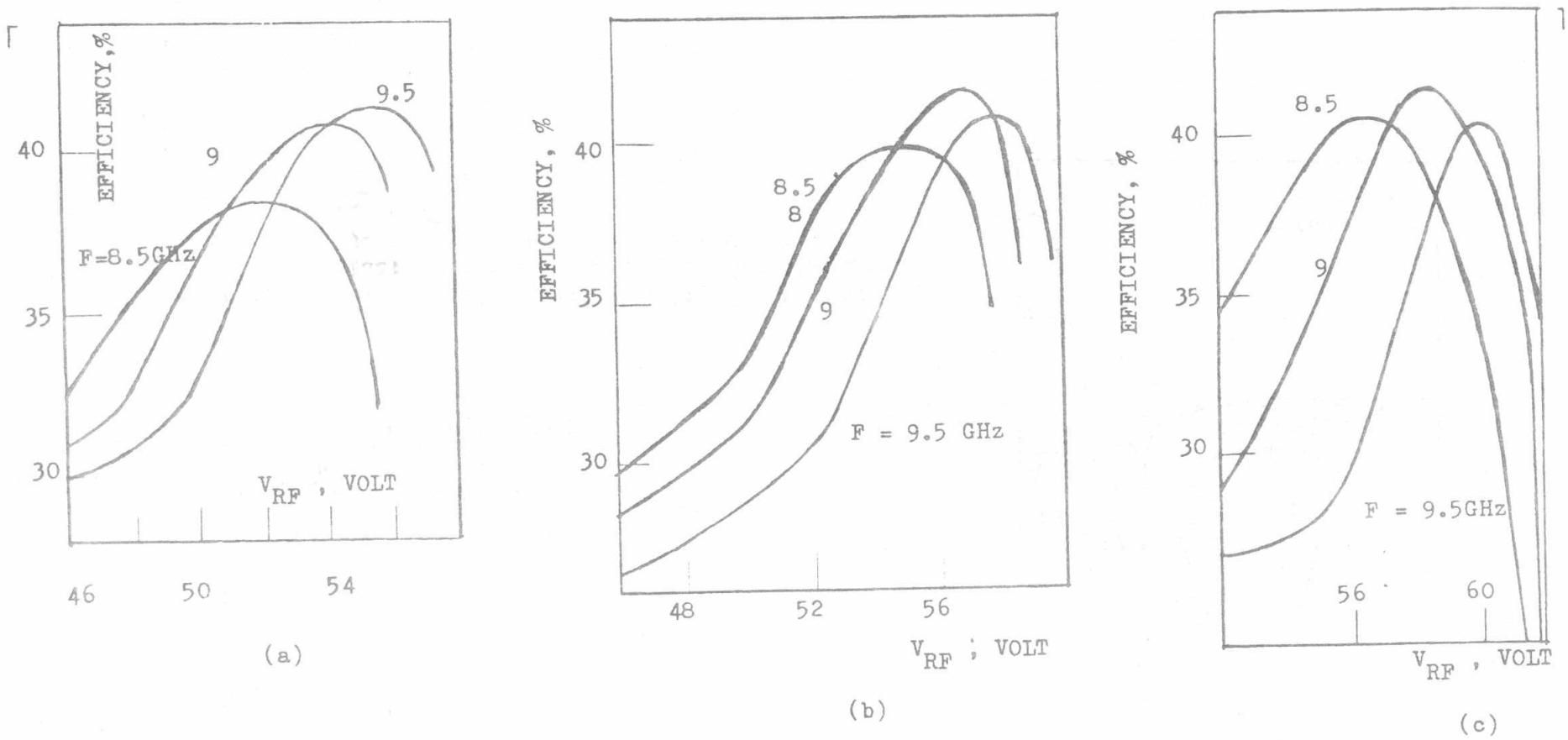
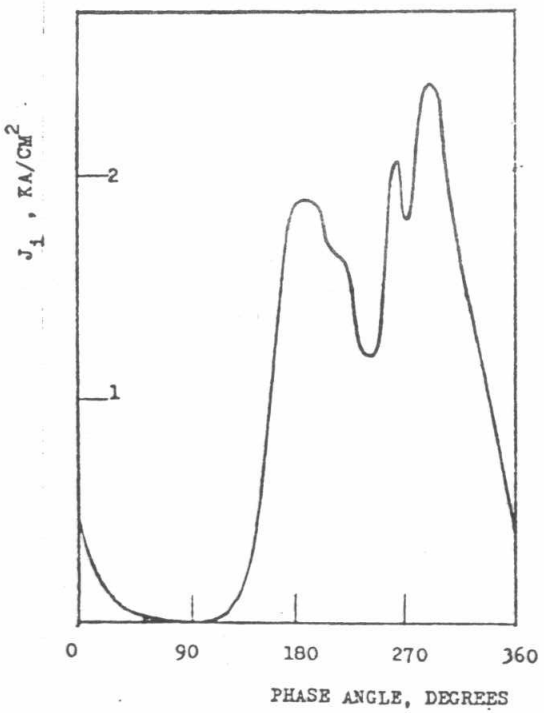


Fig.1 : The efficiency vs. the RF-voltage level V_{RF} for the diodes D1, D2, D3, and D4 respectively.



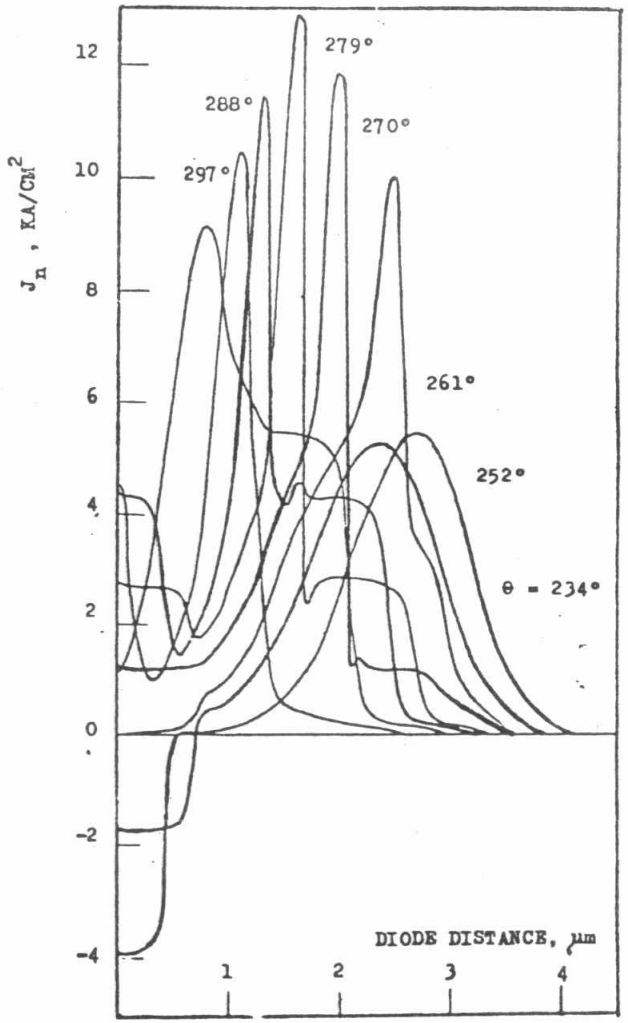


Fig.3 : The induced current density J_i and the electron current density J_n for the diode D3. (J_{dc} = 1000 A/cm^2, F = 9 GHz, V_{RF} = 57 V.)

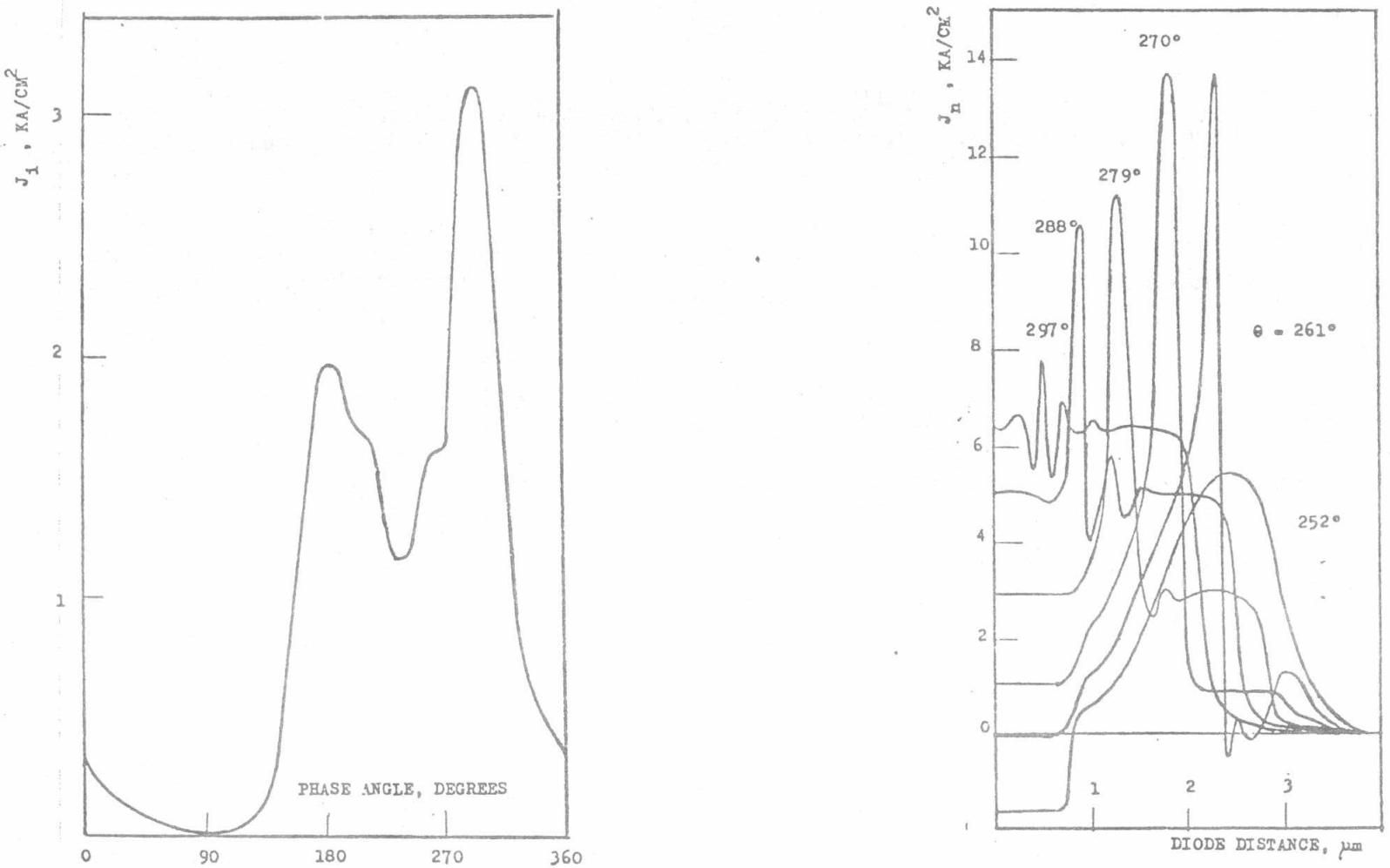


Fig.4 : The induced current density J_i and the electron current density J_n for the diode D3. (J_{dc} = 1000 A/cm^2, F = 9 GHz, V_{RF} = 58 V.)

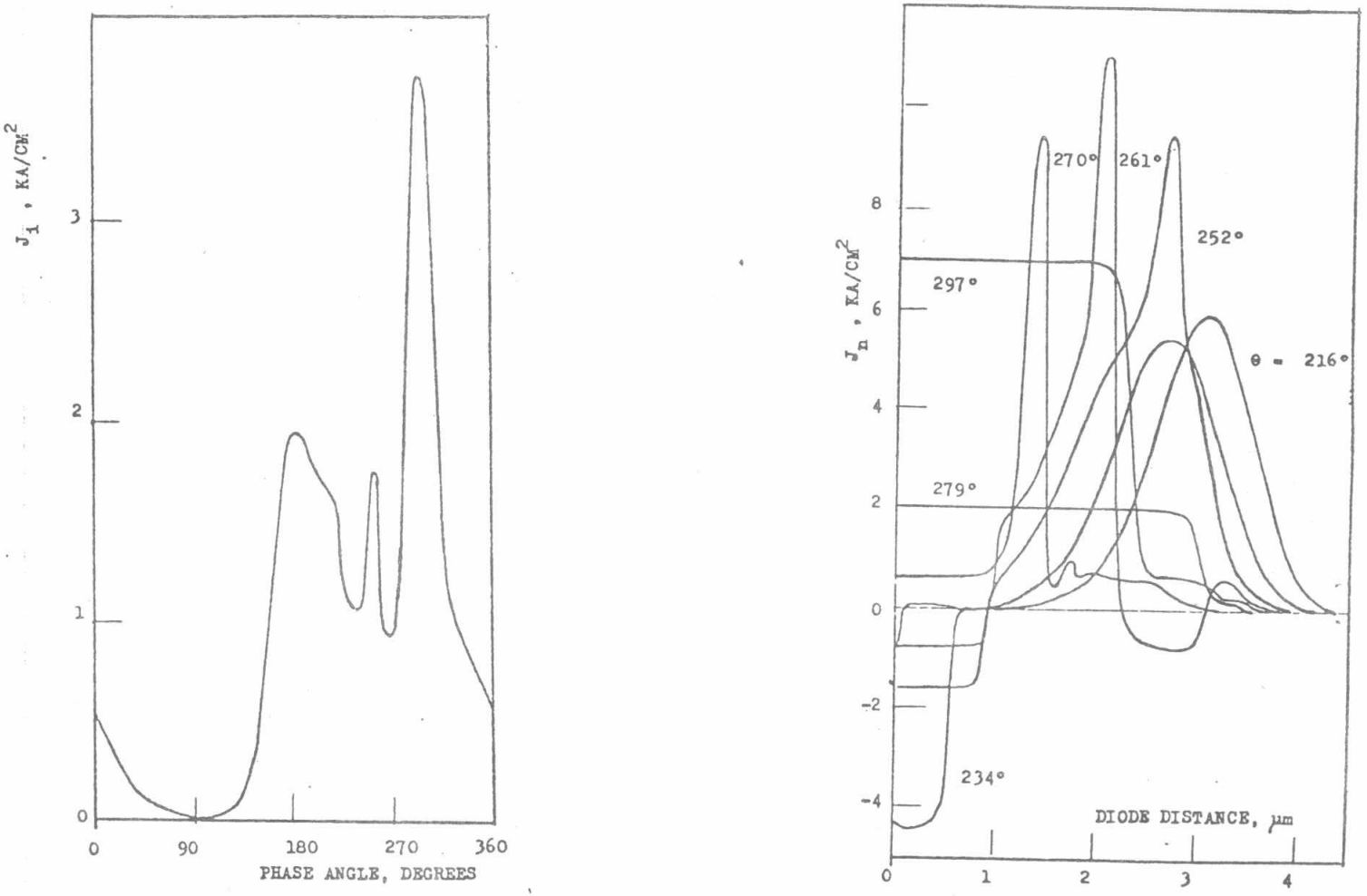


Fig.5 : The induced current density J_i and the electron current density J_n for the diode D3.
(J_{dc} = 1000 A/cm^2 , F = 9 GHz , V_{RF} = 60 V.)