A PROPOSED METHOD FOR IMPROVING
THE PERFORMANCE OF P-TYPE GaAs IMPATT

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Abstract: A special waveform is proposed and assumed to be the optimum waveform for p-type GaAs IMPATTs. This waveform is deduced after careful and extensive study of the performance of these devices. The results presented here indicate the superiority of the performance of the IMPATTs driven by the proposed waveform over that obtained when the same IMPATTs are driven by the conventional sinusoidal waveform. These results are obtained using a full-scale computer simulation program that takes fully into account all the physical effects pertinent to IMPATT operation. In this paper, it is indicated that the superiority of the proposed waveform is attributed to its ability to reduce the bad effects that usually degrade the IMPATT performance such as the space-charge effect and the drift-velocity dropping below saturation effect. The superiority is also attributed to the ability of the proposed waveform to improve the phase relationship between the terminal voltage and the induced current.

Key Words: Computer-Aided Design, GaAs IMPATT, Microwave Engineering

1. INTRODUCTION

It is well known that the performance of n-type GaAs IMPATT diodes is superior to that of p-type diodes [1-3]. This is attributed mainly to the velocity-field characteristic of electrons in the GaAs material that has a negative-differential mobility region [1-3]. This allows the electrons to have higher velocities at the lower values of field encountered in the active region during the negative half cycle of operation. This is in contrast to holes whose velocity drops below the saturated drift velocity for the lower values of the field. Since these effects are inherent in GaAs material, it is only possible to improve the performance of p-type GaAs IMPATTs through modifying the microwave circuit where the diode is imbedded. Since it has been previously reported that the performance of IMPATTs could be improved if it is driven by a non-sinusoidal voltage waveform [4-6], the external circuit attached to the diode must be capable of supporting such waveforms. However, no comprehensive study has been conducted for determining the optimum waveform. In this paper, a systematic procedure for choosing the optimum waveform and designing the external microwave circuit is presented. A special waveform is proposed to be the optimum waveform for p-type GaAs IMPATT. This proposition is supported by an extensive investigation of

IMPATT operation. This investigation has been conducted using a full-scale computer simulation program that takes fully into account all the physical effects pertinent to IMPATT operation without resorting to approximations that limits the scope of its application. This program is a modified version of one described elsewhere [7].

The performance of a given IMPATT that is expected to be modest is studied when it is driven by this waveform and when it is driven by the conventional sinusoidal waveform. Then the results obtained for the two cases are compared. The superiority of the proposed waveform (PWF) is demonstrated especially at higher values of the dc current density J_{dc}. The PWF can be optimized further through optimizing its parameters. Since the PWF is difficult to be realized practically, the performance of the IMPATT is studied when it is driven by the waveform V_2. This waveform comprises only the first two harmonics of the proposed waveform. The performance in this case is found also to be much superior to the conventional case.

2. THE PROPOSED WAVEFORM

The proposed waveform (V_F) is shown in Fig. 1 for the case where $A_2 = 90$ V. In the first part of the cycle, ϕ_1, the height of the PWF is A_1. In the second part, ϕ_2, the height is A_2. In the negative half cycle the height is A_3. The width of the transitions between the different parts is ε_1, ε_2, and ε_3. The waveform consisting of the first two harmonics of the proposed waveform denoted by V_2 is shown in the same figure together with the conventional waveform (V_C). The parameters of this waveform can be optimized according to the following guidelines that are deduced from our extensive study of IMPATT operation [1,2,7-10]:

1. ε_1 should be as small as possible to reduce the spread of transit times of charge carriers.

2. ε_2 should be as small as possible to increase the slope of the terminal voltage when crossing the breakdown level. This helps reduce the space charge effect and improve the phase delay provided by the avalanche process.

3. A_1 should be null to reduce the power dissipation at the beginning of the RF cycle.

4. The choice of ϕ_2 and A_2 is a compromise between the following factors:
   a. ϕ_2 should be minimized in order to reduce the spread of transit times of carriers.

b. A_2 must be increased to reduce the space charge effect and the spread of transit times of carriers and to satisfy the breakdown condition. However, A_2 must not be too high, lest the breakdown condition should be satisfied only by an excessive increase of the dc-breakdown voltage. This is attributed to the saturation of the ionization rates at the high values of electric field.

c. The product $\phi_2 A_2$ must be as high as possible to enable the increase of A_3, which improves the performance.

5. The choice of ϕ_3 and A_3 is a compromise between the following factors:

a. A_3 must be sufficiently high in order to extract the maximum energy from the drifting carriers but must not be too high so as to cause the carrier drift velocity to drop below the saturated value.

b. ϕ_3 must be reduced to delay the injection of the avalanche-generated packet (AGP) in the drift region; but if ϕ_3 is excessively reduced, the conductance of the diode may become positive at some higher order harmonics. The effect of the parameter A_2, and consequently A_3, will be presented in this paper.

3. THE RESULTS OBTAINED FOR THE CHOSEN IMPATT

The IMPATT whose performance will be studied is a GaAs p-type one having a single-drift abrupt junction structure. The doping density in the drift region is 5×10^{15} cm^{-3} and its width is 3.7 μm.

The PWF has the following parameters:

$$\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 9^o, \Phi_1 = 72^o, \Phi_2 = 90^o,$$

$$\Phi_3 = 171^o, A_1 = 90\,\text{V, and } A_2 = 49.5\,\text{V}.$$

Figures 2 and 3 show, respectively, the efficiency and the RF power density versus the dc current density J_{dc} for the PWF and a sinusoidal signal of amplitude 70 V. The value of 70 V is chosen since it gives the best performance for the sinusoidal excitation at the highest values of J_{dc} considered.

Figures 4 and 5 show the efficiency and the RF power for the waveform V_2 consisting only of the first two harmonics of the PWF. The results indicate clearly the superiority of the proposed waveforms over the conventional sinusoidal signal especially at the higher values of the dc bias current where the efficiency becomes almost three times higher and the RF power six times higher for the PWF. This demonstrates the ability of the proposed waveforms to reduce considerably the space-charge effect. This is illustrated clearly in Fig. 6, which shows the induced current J_i for the proposed waveform and the sinusoidal signal at different values of the dc bias current for the PWF and the sinusoidal signal. It is clear that the major manifestation of the reduction of the space charge effect

is the delay of the injection of the avalanche-generated packet in the drift region (DR). This means that the time delay provided by the avalanche process is increased. This contributes to the improvement of the performance. The performance is also improved by reducing the spread of the transit times of carriers. This causes the AGP and consequently the peak of J_i to be sharper, as the figures show. Hence, J_i has higher values for the PWF during the negative half cycle. This is attributed also to the reduction of the drift velocity dropping below the saturation (VDBS) effect. On the other hand, the shape and the values of the induced current in the negative half cycle are better for the proposed waveforms. This is attributed to the reduction of the spread of transit times of carriers for the PWFs. The reduction of the spread of transit times of carriers means that the generated pulse of holes will be more localized in both the time domain and the space. This is clearly demonstrated in Fig. 7 that shows the spatial distribution of the hole current density for the considered waveforms at different phase angles. As it is seen at the beginning of the RF cycle, some carriers from the previous cycle are still being extracted at the ohmic contact. The extraction of these carriers is carried out earlier for V_F. Hence, the start of the avalanche breakdown is considerably delayed for the proposed waveforms. This contributes to their better performance since the phase delay provided by the avalanche process is enhanced. The injection of the AGP of holes is also delayed for the proposed waveform. Correspondingly, the phase delay is increased. This effect considerably improves the performance. As the AGP of holes drifts toward the ohmic contact it is dispersed by the effect of diffusion. This dispersion is enhanced by the space-charge effect for V_C. For V_F, the dispersion is smaller. This is attributed to two facts: that the AGP is sharper in both the space and the time domain, and the space-charge effect is less significant for the PWF. The reduction of the spread of transit times means that the currents induced by the carriers have a better distribution of phase angles. Consequently, the induced current will be higher. The drift-velocity dropping below saturation is less significant for V_F. This causes almost all the holes to drift at the saturated velocity. Hence, the induced current is higher and more flat for this waveform. This contributes to its better performance.

Figures 8 and 9 show the spatial distribution of the electron current (J_n), and the spatial distribution of the electric field E at different phase angles for different values of dc current. By analyzing these results, it is clear that the AGP, after being injected into the drift region, causes E to decrease behind it and to increase in its front. This effect becomes more significant as J_{dc} increases. The decrease of the field behind the AGP causes the avalanche generation to be suppressed early in the cycle, which reduces the spread of the transit times of the carriers and causes the peak of J_i to be sharper. Hence, the performance is improved. The increase of the field in the front of the AGP suppresses the VDBS effect. Hence, J_i will have higher values during the negative half cycle and the efficiency is enhanced. The figures show also that J_i is extremely

small during the major portion of the positive half cycle for the PWF. This is attributed to the shape of the PWF and helps improve the efficiency.

Figures 10 and 11 show the effect of A2 on the performance of the p-type IMPATT. The increase of both the RF power and the efficiency with A_2 is attributed mainly to the reduction of the space charge
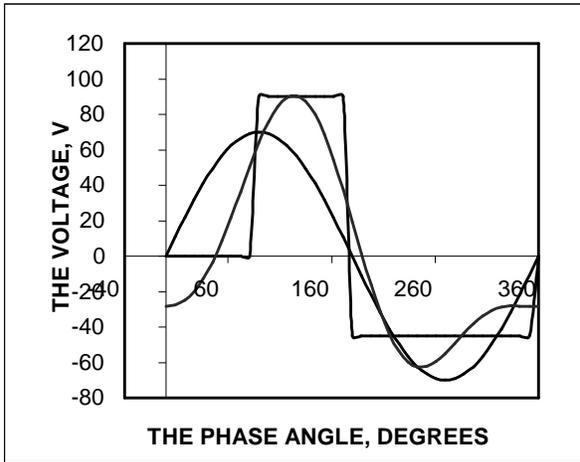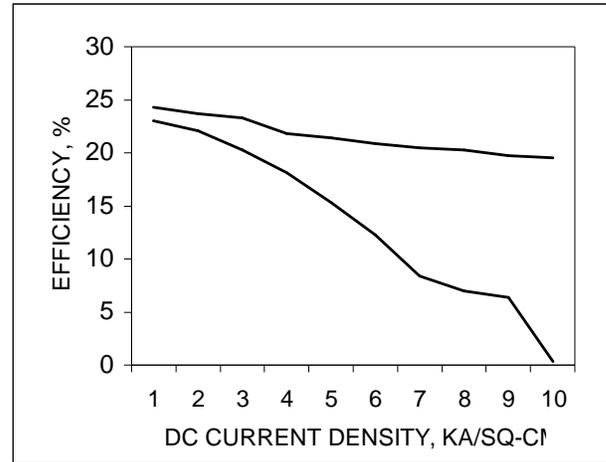
Fig.1 The voltage waveforms VC, VF, and VS
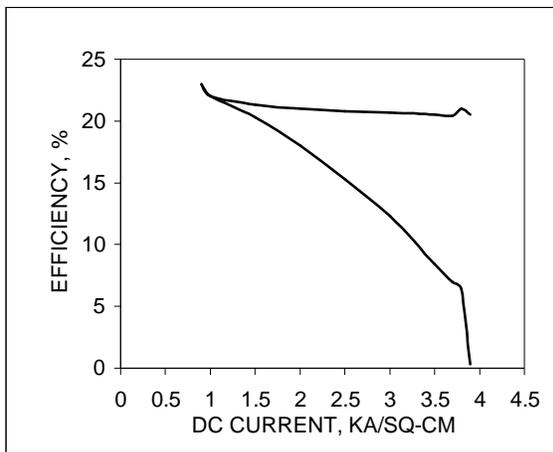
Fig. 2 The efficiency versus DC current for V_F and V_C at F=9 G Hz

Fig. 3 The RF power versus DC current for V_F and V_C

Fig. 4 The efficiency versus DC current density

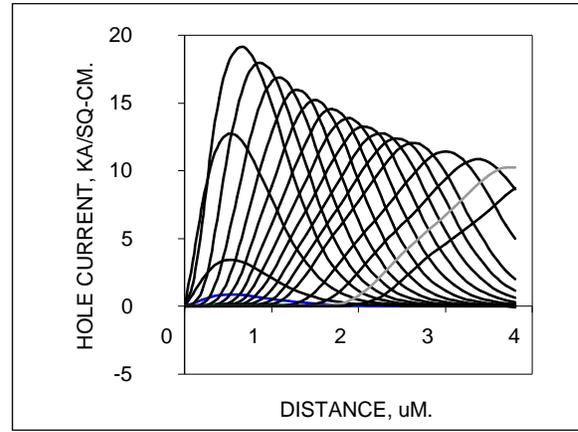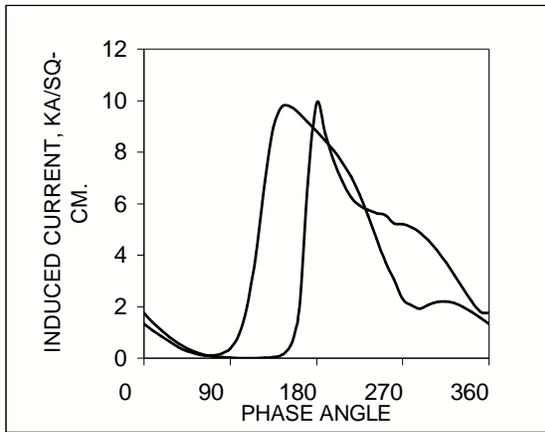**Fig. 5** RF power versus DC current for V_2 and V_C at F=9 G Hz
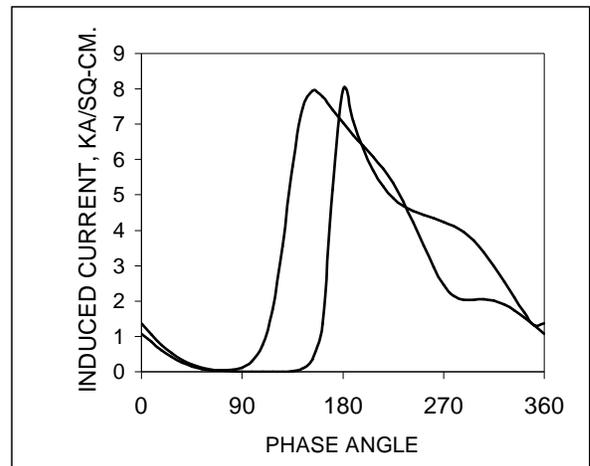
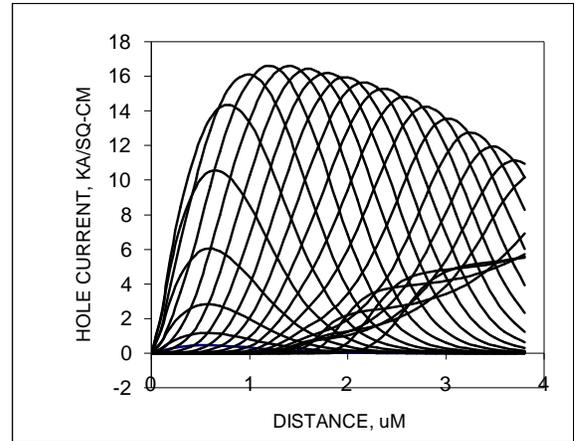**Fig. 6A** The induced current for V_F and V_C at J_{DC}=3 KA/cm^2
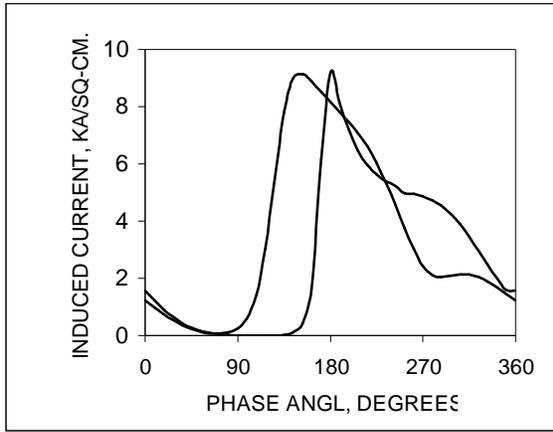
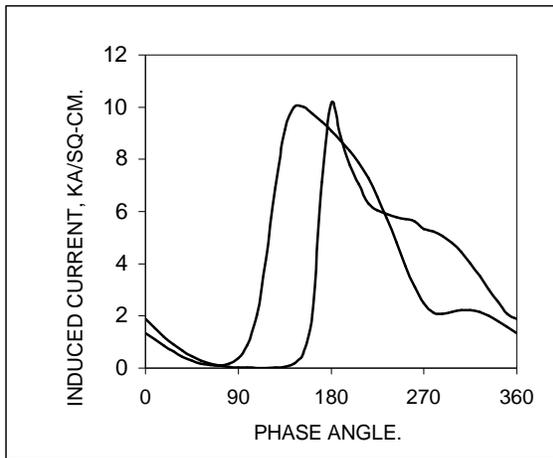**Fig. 6B** The induced current for VF and VC at JDC=3.5 KA/cm2

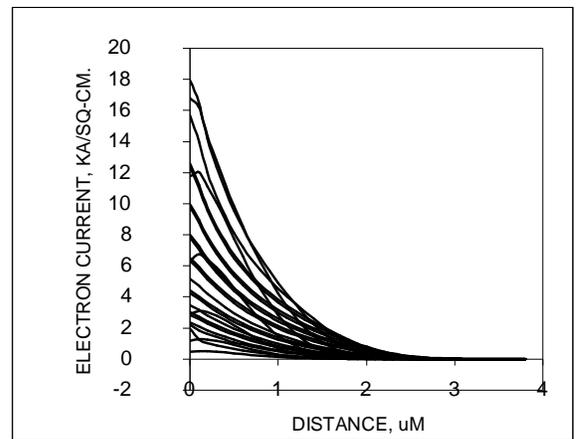**Fig. 7A** The hole current versus distance for VF at JDC = 3.5 KA/cm2

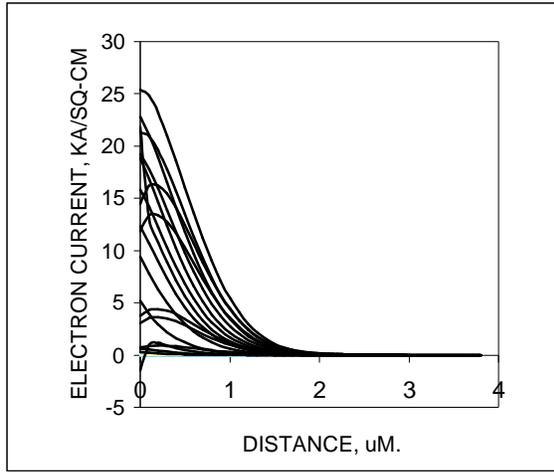**Fig. 6C** The induced current for V_F and V_C at J_{DC}=3.8 KA/cm^2

Fig. 7B The hole current versus distance for VC at JDC = 3.5 KA/cm2
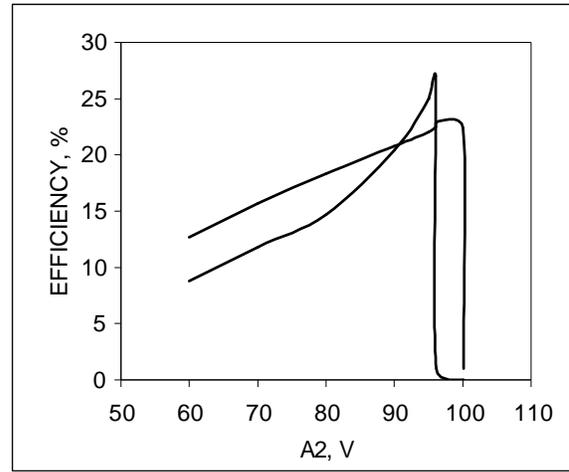

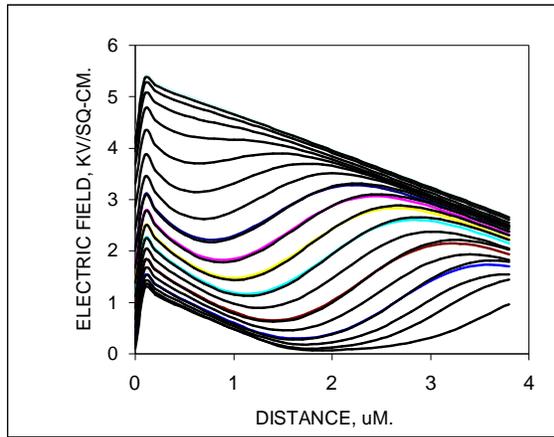**Fig. 6D** The induced current for V_F and V_C at J_{DC}=3.9 KA/cm^2

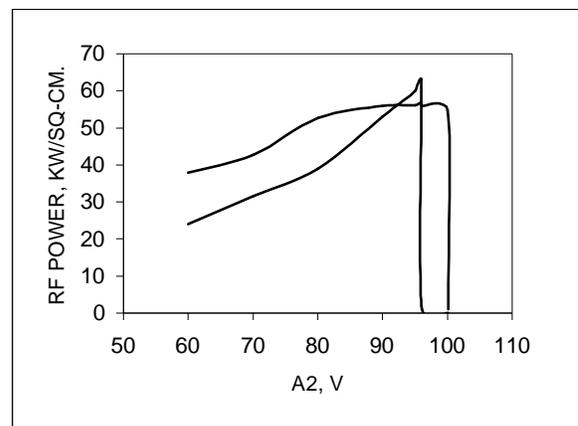**Fig. 8A** The electron current versus distance for VC at JDC = 3.5 KA/cm2

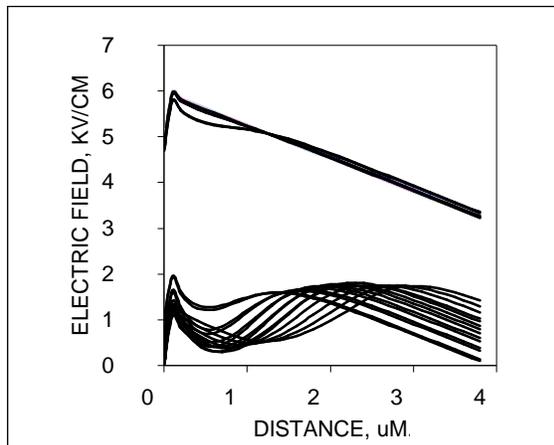**Fig. 8B** The electron current versus distance for V_F at J_{DC} = 3.5 KA/cm^2

Fig. 9A The electric field versus distance for V_C at J_{DC} = 3.5 KA/cm^2

Fig. 9B The electric field versus distance for V_F at J_{DC} = 3.5 KA/cm^2

Fig. 10 The efficiency versus A_2

Fig. 11 The RF power versus A_2

effect and the reduction of the spread of transit times of holes. Since the increase of A_2 causes A_3 to increase, the improved performance is attributed also to the reduction of the minority carrier enhancement effect and to the fact that energy extracted in the DR increases with A_2 and A_3. The saturation and decrease of the power and the efficiency for the large values of A_2 are attributed to the drift velocity dropping below saturation and the saturation of the ionization rates at higher electric fields.

4. THE REASONS LEADING TO THE SUPERIORITY OF THE PROPOSED WAVEFORMS

The superiority of the performance of the IMPATTs driven by the proposed waveforms is attributed to the following reasons:

1. The considerable reduction of the space charge effect. This is attributed to the high value of the slope of the terminal voltage when crossing the breakdown level and to the large value of this voltage in the time interval during which the avalanche breakdown takes place.

2. The generation of minority carriers in the drift region is diminished. This is attributed to the higher magnitude of RF voltage during the negative half cycle.

3. The phase delay provided by the avalanche process is increased. This is because both the start of this process and the injection of the AGP in the drift region are delayed. This is attributed to the favorable shape of the proposed waveform and its ability to reduce both the space-charge effect and the minority-carrier enhancement effect. Therefore, the phase relationship between the terminal voltage and the induced current is improved.

4. The reduction of the spread of transit times of carriers. This is also attributed to the shape of the proposed waveform that helps reduce both the space charge effect and the minority carrier enhancement effect. The proposed waveform causes the carrier generation by the avalanche multiplication to be localized in the time and the space domains.

5. Both the drift-velocity dropping below saturation and the depletion-layer width modulation effects are reduced. This is because of the higher optimum values of the operating dc bias current.

5. CONCLUSION

In this paper, the performance of the p-type GaAs IMPATT is studied when it is driven by a proposed non-sinusoidal waveform. It is indicated that by using this waveform, the bad effects that usually degrade the IMPATT performance are reduced. These bad effects include the space-charge effect, the drift-velocity dropping below saturation effect, and the minority-carrier enhancement effect. It is also illustrated that the proposed waveform helps increase the phase delay provided by the avalanche process and reduce the spread of transit times of carriers. All these factors contribute to the superiority of the proposed waveform over the conventional one. The performance is also studied when the p-type GaAs IMPATT is driven by waveforms consisting only of the first two or three harmonics of the proposed waveform. In this case, the performance of the IMPATT is found superior to that obtained when the device is driven by the conventional waveforms.

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BIOGRAPHY

Dr. Hosny Ahmed El-Motaafy was born in 1951, at Cairo, Egypt. He got his B.Sc. and M.Sc. degrees in Electronic Engineering in 1974 and 1979, respectively, from MTC (Military Technical College), Cairo, Egypt and his Ph.D. from ENSAE (Ecole Nationale Supérieure de l'Aéronautique et de l'Espace), Toulouse France, in 1982. Dr El-Motaafy research interest is in microwave electronics and active integrated antennas where he has more than 70 publications. Currently, he holds a position of Associate Professor at the "Higher Technological Institute (HTI)", 10th of Ramadan City, Cairo, Egypt.