Analysis of p-type GaAs IMPATT diodes driven by non-sinusoidal voltage waveforms

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A non-sinusoidal waveform, that can be used to increase the output power and the efficiency of p-type GaAs IMPATT diodes, is presented. This waveform comprises two properly chosen harmonics that can be supported by a passive circuit. The waveform is deduced after careful and extensive study of the performance of these devices. The obtained results clearly 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 the physical effects pertinent to IMPATT operation. It is indicated that the superiority of the proposed waveform is attributed to its ability to reduce the undesirable 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 reduce the spread of transit times of carriers.

تقدم هذه الورقة شكلا موجيا غير جيبى يمكن استخدامه لزيادة قدرة خرج وكفاية ثنائيات أرسنيد الجاليوم الأمباتية من النوع p. ويحتوى هذا الشكل الموجى توافقيتين تختاران بطريقة صحيحة بحيث يمكن أن تدعمهما دائرة خاملة. ولقد أستنتج هـذا الشـكل الموجى بعد دراسة مستفيضة لاداء هذه الثنائيات . وتوضح النتائج التى حصل عليها بجلاء تفوق هذه النبائط عند حفزها بالشكل الموجى المقترح مقارنة بأدائها عند حفزها بالشكل الموجى التقليدى. وتم الحصول على هذه النتائج بأستخدام برنـامج محاكـاة حاسوبى كامل يأخذ فى الاعتبار كل الظواهر الفيزيائية المتعلقة بأداء الثنائى. ولقد أتضح أن تفوق الشكل الموجي المقترح يعزى الىمقدرته على تقليل التأثيرات غير المرغوب فيها والتى تهبط بأداء الثنائى مثل تأثير شحنة الحيز وتأثير هبوط سرعة الانسياق الى ما تحت التشبع. كما يعزى هذا التفوق أيضا الى مقدرة الشكل الموجى المقترح على تقليل تشتت زمن عبور الحاملات.

Keywords: IMPATT diodes, p-type GaAs, Non-sinusoidal voltage waveforms for IMPATTS

1. Introduction

The optimum voltage waveform for p-type GaAs IMPATT diodes is proposed elsewhere [1]. This proposition is supported by an extensive investigation of IMPATT operation [2-4]. This optimum waveform is presented here in Fig. 1. a where it is denoted by VF. It is proved that this waveform can be used to increase considerably the output power and efficiency of p-type IMPATTs [1]. However, this waveform is very difficult to realize practically because the microwave circuit where the diode is imbedded must be capable of supporting all the harmonics forming it.

It has been previously reported that the performance of IMPATTs could be improved if it is driven by a non-sinusoidal voltage waveform comprising harmonically related components [5-9]. However, no comprehensive study has been conducted for determining the optimum combination of these harmonics and their phases. In this paper, we propose that the optimum non-sinusoidal waveform should comprise some of the first harmonics of the waveform presented in [1]. Hence, a systematic procedure for improving the performance of p-type GaAs IMPATTs can be developed. 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 limit the scope of its application. This program is described elsewhere [10].

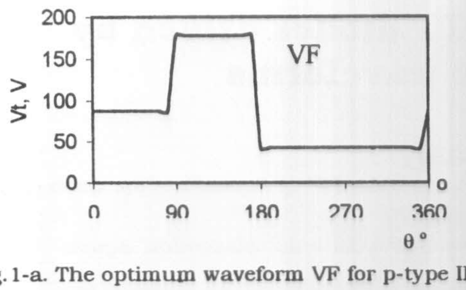


Fig. 1-a. The optimum waveform VF for p-type IMPATT.

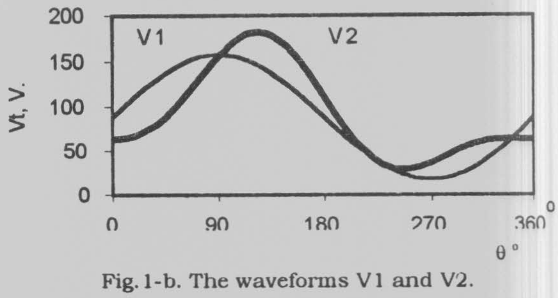


Fig. 1-b. The waveforms V1 and V2.

The performance of a given IMPATT, that is expected to be modest, is studied when it is driven by a waveform consisting only of the first two harmonics of the waveform VF 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, is demonstrated specially at the higher values of the dc current density J_{dc}

2. Results

The IMPATT diode 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^{17} cm^{-3} and its width is $3.9\,\mu$m. The operating frequency is taken as 9 GHz. The waveform (VF) that is proposed elsewhere [1] is shown in Fig. 1a. It is indicated in [1] that this waveform gives a performance that largely surpasses that obtained when the conventional sinusoidal signal is used. The waveform consisting of the first two harmonics of the proposed waveform denoted by V2 is shown in Fig. 1-b together with the conventional sinusoidal waveform V1. The amplitude of the waveform V1 is chosen to be 70 V. This value is chosen since it gives the best performance at the highest values of J_{dc}. The parameters of the proposed waveform can be optimized according to the guidelines mentioned in [1]. These guidelines are deduced from our extensive study of IMPATT operation [2-4,8-10]. The results presented here are obtained at a dc bias current J_{dc} of 3.5 kA/cm^2. This value is chosen in order to illustrate the ability of the proposed waveform V2 to reduce the space charge (SC) effect. It is to be noticed that the dc voltage V_{dc} is smaller for V2. This is attributed to the fact that V2 attains higher values during the portion of the cycle where the avalanche breakdown takes place. Hence, it is possible to satisfy the breakdown condition by smaller values of V_{dc}. This contributes to the smaller dc power dissipation and correspondingly the better efficiency obtained when the IMPATT is driven by V2. The slope of V2 when crossing the breakdown level is also higher. This contributes to its better ability to reduce the SC effect. Fig. 2 shows the efficiency η versus J_{dc} for the two waveforms. It is seen that the efficiency for V2 remains higher for all the values of J_{dc} considered. The degradation of η with J_{dc} is considerably more pronounced for V1. This indicates the better ability of V2 to reduce the SC effect. It is to be noticed that the efficiency is almost three times higher for V2 at J_{dc} = 4 kA/cm^2.

Figure 3 shows the output RF power, P_{rf}, for the two waveforms. It is seen that P_{rf} remains higher for V2 and its increase with J_{dc} is more pronounced. The optimum value of J_{dc}

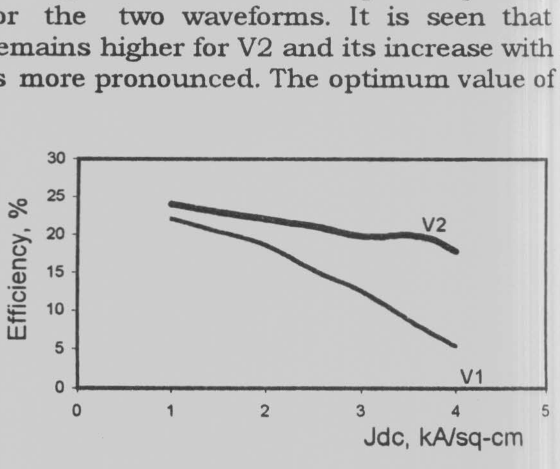


Fig. 2. Efficiency η vs. dc current J_{dc}.

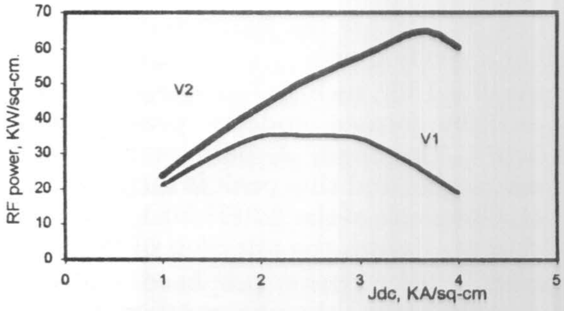


Fig. 3 RF power P_{rf} vs. dc current J_{dc}.

for V2 is 3.75 kA/cm² versus 2.5 kA/cm² for V1. Also, P_{rf} is almost three times higher for V2 at the highest values of J_{dc} considered. The reasons leading to the superiority of the proposed waveform over the conventional one will become clear after considering the behavior of the charge carriers and the electric field in the IMPATT for the two waveforms.

3. Analysis

Figure 4 shows the induced current J_i for the proposed waveform V2 and the sinusoidal signal V1 at J_{dc} = 3.5 kA/cm². It is seen that the peak of J_i occurs exactly at 180° for V2 versus 153° for V1. Hence, the time delay provided by the avalanche process is higher for V2. This contributes to the better performance of V2. This greater phase delay is attributed to the better ability of V2 to reduce the SC effect, which causes the avalanche process to be shut down early in the cycle. On the other hand the shape and the values of the induced current in the negative-half cycle are better for V2. This is attributed to the reduction of the spread of transit times of carriers for this waveform. It is attributed also to the higher velocities of charge carriers during this portion of the cycle. Hence, the drift velocity dropping below saturation is less pronounced for V2. These effects causes P_{rf} to be higher for V2. On the other hand, the values of J_i at the end of the cycle are slightly higher for V2. This means that the density of carriers that are not extracted during the negative half cycle is slightly higher for V2. However, this effect is not significant since these carriers will be extracted at the beginning of the next cycle where the values of V2 are very small.

Figure 5 shows the hole current J_p (thick line) and the electric field E (thin line) at θ = 90° . It is seen that the avalanche generation

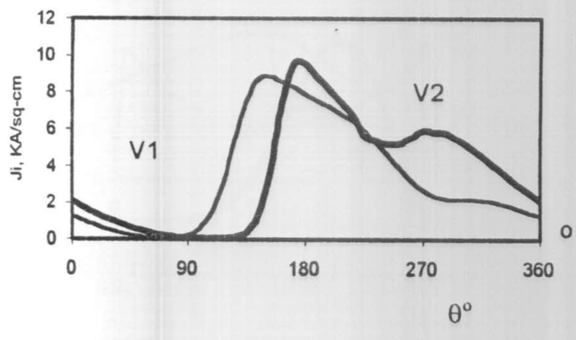


Fig. 4 Induced currents for V1and V2.

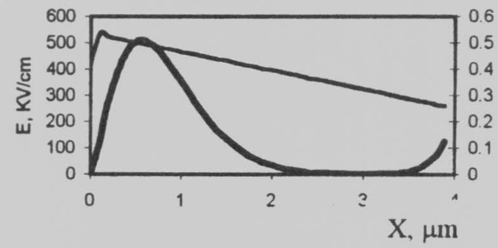


Fig. 5-a. Hole current and electric field for V1 at θ= 90 °

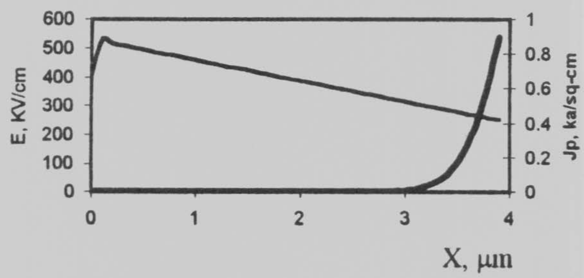


Fig. 5-b. Hole current and electric field for V2 at θ = 90°.

has already started for V1 whereas some holes are still being extracted at the ohmic contact. For V2, the avalanche generation has not started yet and a relatively large portion of the holes generated in the previous cycle are still being extracted.

At θ = 153°, as Fig. 6 (a, b) shows, the avalanche generated packet of holes (AGPH) has already been formed and injected into the drift region (DR) for V1. The peak of the AGPH is at a diode distance X that is equal to 1.2 μm. The value of this peak is about 16.5 kA/cm^2. Thus, J_i has its peak at θ = 153°. The SC effect of the AGPH reduces the electric field (E) behind the packet and increases it in its front. Hence, the avalanche generation is shut down early. Due to the relatively high values of E in the DR some carriers are generated there. Therefore, the spread of transit times of carriers is increased and the performance is degraded. For V2, the AGPH is still growing and its SC effect is not significant. The peak is still at X = 0.6 X, μm

At θ = 180°, as Fig. 7 shows, the AGPH for V2 is fully formed and its peak is about 20 kA/cm^2. Therefore, J_i has its peak at this phase angle and this peak is larger than that of V1. The peak of the AGPH for V2 is still at X = 1 μm. Hence, the injection of the AGPH is delayed for the proposed waveform. Correspondingly, the phase delay provided by the avalanche process is increased. This effect improves considerably the performance. The AGPH for V2 is sharper than that for V1, which is dispersed by the effect of diffusion. Hence, the spread of transit times of carriers is more pronounced for V1. This results in a degraded performance for this waveform. This degradation is enhanced by the generation of carriers in the DR near the last quarter of the diode.

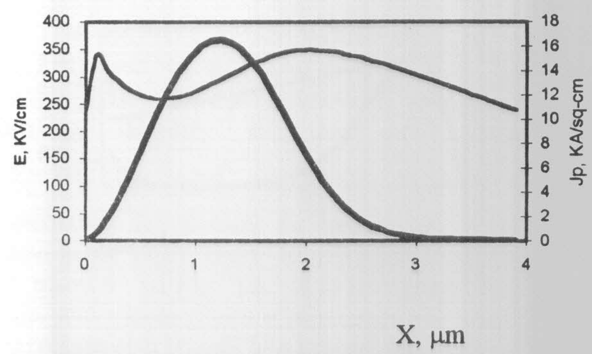


Fig. 6-a. Hole current and electric field for V1 at θ = 153°.

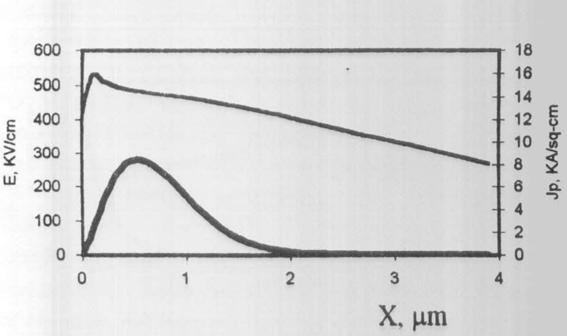


Fig. 6-b. Hole current and electric field for V2 at θ = 153°.

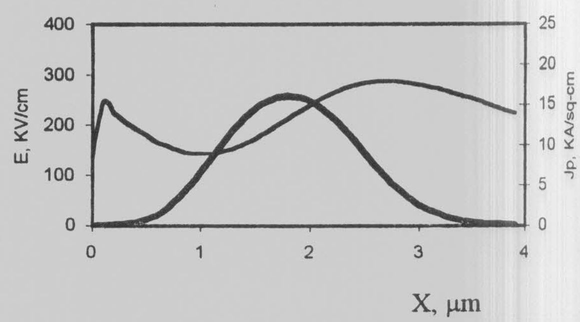


Fig. 7-a. Hole current and electric field for V1 at θ = 180°

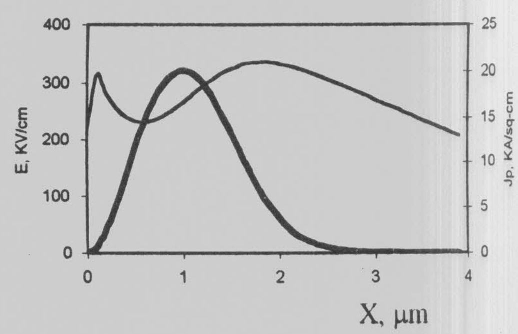


Fig. 7-b. Hole current and electric field for V2 at θ = 180°.

At θ = 279°, as Fig. 8 (a,b) shows, the AGPH is being extracted for V1. However, the holes constituting the tail of the AGPH are slowed down in the DR because of the low values of the electric field E there. These two effects cause J_i to have a low value at this phase angle. For V2, the peak of the AGPH is still at X = 2.9 μm. This peak is very high. This improves the performance for V2.

At θ = 324°, as Fig. 9 (a, b) shows, the AGPH is still being extracted for V1. The hole current for V2 has higher values. This causes J_i to have higher values for V2 during the remaining portion of the cycle. This contributes to the better performance of V2.

At the end of the cycle, as indicated in Fig. 10 (a, b), the number of carriers that are still being extracted is higher for V2 causing J_i to be higher for V2 at the beginning of the next RF cycle.

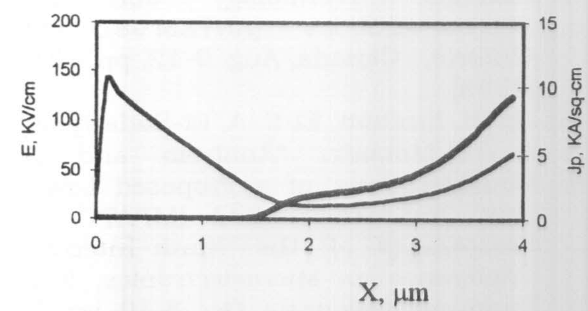


Fig. 8-a Hole current and electric field for V1 at θ = 270°.

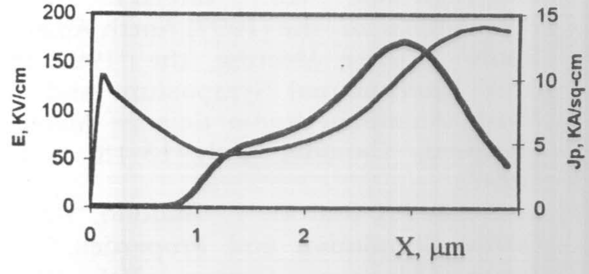


Fig. 8-b. Hole current and electric field for V2 at θ = 270°.

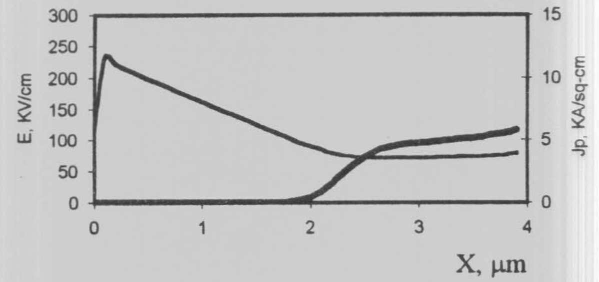


Fig. 9-a. Hole current and electric field for V1 at θ = 324°.

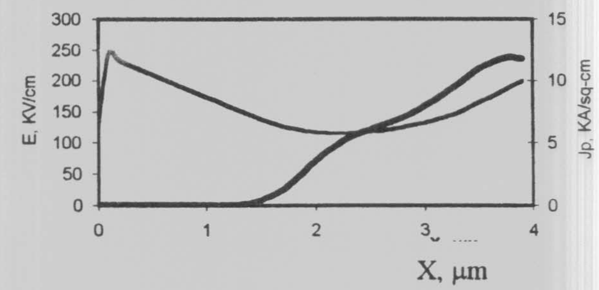
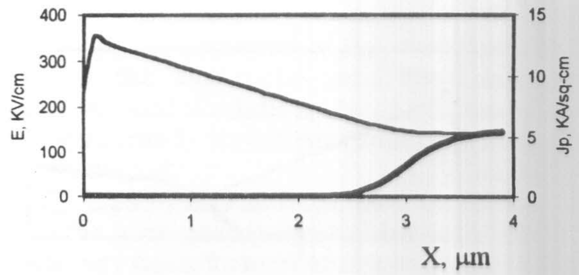


Fig. 9-b. Hole current and electric field for V2 field at θ=324°

It is to be noticed that during the negative half cycle, the drift-velocity dropping below saturation is less significant for V2. 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 the better performance obtained for V2.

4. Operation of the IMPATT as a frequency doubler

It is to be noticed that the conductance of the IMPATT at the second harmonic is negative. Hence, it is possible to design a passive circuit supporting the waveform V2. In addition, it is possible to use the IMPATT driven by V2 as a frequency doubler. For example, at J_{dc} = 3 kA/cm², the output power is 8.8 kW/cm², the efficiency is 3 % at the second harmonic, namely at a frequency of 18 GHz. The conductance at this frequency is −21.2 S/cm². This means we can use an



X, μm

Fig. 10-a. Hole current and electric field for V1 at θ

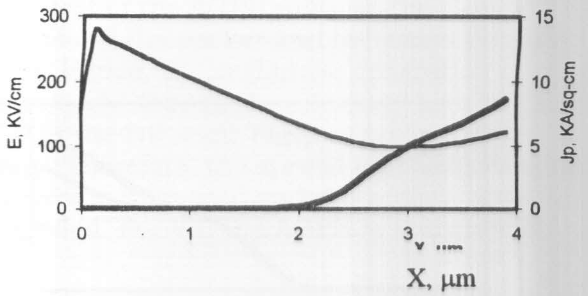


Fig. 10-b. Hole current and electric field for V2 at θ = 360 °

IMPATT diode designed to operate at 9 GHz to generate microwave power at 18 GHz. This is an important result taking into account the fact that the IMPATT diode designed to operate at a lower frequency is less expensive and has a higher cross sectional area. The use of the IMPATT diode driven by the proposed waveform V2 as frequency doubler is extensively studied and the results will be the subject of a subsequent paper.

5. Conclusions

In this paper, the performance of the p-type GaAs IMPATT diode is studied when it is driven by a proposed non-sinusoidal waveform. This waveform can be obtained systematically since it consists of the first two harmonics of the previously known optimum waveform for p-type GaAs IMPATTs. It is concluded that using this waveform reduces the undesirable effects that usually degrade the IMPATT performance. These effects include the space-charge effect, the drift-velocity dropping below saturation effect, and the carrier generation into the drift region. 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 IMPATT diode driven by the proposed waveform can also be used as a frequency doubler.

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