"THE BEHAVIOR OF A PULSED MILLIMETER WAVE (70 GHZ) IMPATT DIODE OSCILLATOR DURING LASER ILLUMINATION"

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SUMMARY

The effect of photon injection on a 70-GHz pulsed IMPATT diode was investigated. With the diode mounted in a waveguide oscillator, two useful modes of operation, the "enhancement" mode and the "inhibition" mode, were observed. The enhancement mode permits fast on and off switching (and modulation) of the IMPATT diode oscillator. The inhibition mode permits pulse width control and reduction of undesired intrapulse frequency shift (chirp).

Introduction

It has been previously shown [1-6] that the characteristics of avalanche diodes and other microwave solid-state devices can be influenced by irradiating the active region of the device with photons, high-energy electrons, or other irradiating beams.

We investigated the behavior of a pulsed millimeter-wave (MMW) silicon double-drift (Si DD) IMPATT diode in an oscillator circuit when the diode junction is illuminated by a GaAs laser beam. We report the first observation of optical control of IMPATT diodes at 70 GHz, and discuss several interesting aspects of the investigation. Our objective is to find applications of the effects of photon injection into the MMW IMPATT diode source. The characteristics investigated include intrapulse frequency shift or chirp, noise, pulse jitter, and rise and fall time.

Of particular interest for system applications is the control of the chirp of the pulsed IMPATT diode. Chirp is a highly undesirable effect if uncontrolled, but can be very useful if fully controlled. The goal of this work is a controlled, stable, frequency coherent, and reliably functioning MMW IMPATT diode source that would eliminate or reduce the need for present complex and expensive means of stabilization. The experimental work presented here was performed at 70 GHz, but will be extended to 95 and 140 GHz.

The aspects of photon injection are only briefly outlined here, without theoretical discussion. Theoretical papers published on the subject matter or on closely related topics usually start from Read's original equation.[7] The authors then expand Read's equation by an additional term[1-3,5,6,8-10] describing the effect of the induced, ionizing photocurrent in the active region of the device. The modified Read equations for the electrons and holes are then appropriately modelled; with selected boundary conditions, these lead to an expression for the diode impedance. Finally, in conjunction with the proper circuit analysis, the condition for oscillation with photon injection into the IMPATT diode junction can be established.

Physical Interpretation of the Effect of Photon Injection

The induced (ionizing) photocurrent has in general an undesired, deteriorating effect on the dc to rf conversion; however, if this effect is controlled and cultivated, it can be used advantageously for system applications.

The physical mechanism of the photon injection has been discussed by Misawa[1] and other researchers.[3,5,6,8,9] It has been shown in their analytical studies, and partially verified by experimental work at lower frequencies, that photon injection by a laser beam or injection by a high-energy electron beam[2,10] into the diode junction generates excess carriers; this current component is termed "reverse saturation current." In general, a saturation current of smaller magnitude is generated by thermal effects in the diode; in this discussion, however, a "large" reverse saturation current is purposely generated and effectively utilized. The laser-induced reverse saturation current changes the induced current pulse, $I_o(t)$ into the pulse, $I_o'(t)$, which is shifted in phase and triggers premature avalanching in the active region of the diode (but in a controlled manner).

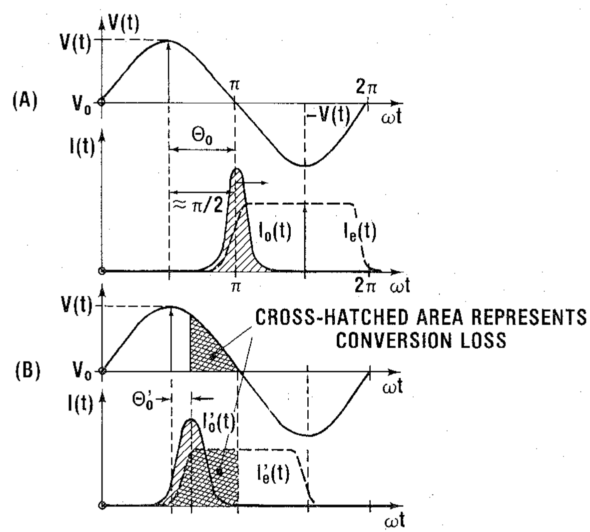

Figure 1: Phase relationship between applied rf voltage and induced avalanche current pulse: (A) without and (B) with photon injection.

The two states of diode operation, with and without photon injection, are illustrated in a simplified form in figure 1. The upper trace (figure 1A) depicts the ideal operational condition (no reverse saturation current) with an ideal pulse shift delay (due to avalanche buildup) of $\Theta_o = \pi/2$ between the applied maximum of the rf voltage $V_{RF}(t)$ across the junction and $I_o(t)$. Associated with $I_o(t)$ is the external $I_e(t)$. $I_e(t)$ flows in the external circuit across the diode, while the induced current pulse $I_o(t)$ drifts through the active region during the negative rf voltage swing with a duration of about π. In the lower trace (figure 1B), showing operation with photon injection, the generated carriers produce the reverse saturation current that causes in turn an advance of $I_o(t)$ and results in $I_o'(t)$, reducing the phase angle $\Theta_o < \pi/2$; this then introduces a resistive, dissipating current component, and thus deteriorates the dc to rf conversion. A further increase of the photon energy level gives rise to additional reverse saturation current, until finally the oscillations cease. Also, as expected, the phase angle change produces a frequency shift due to the reactive component of $I_0^1(t)$. During operation, the pulse sequence between the generated rf pulse and the injected laser pulse can be timed as shown in figure 2.*

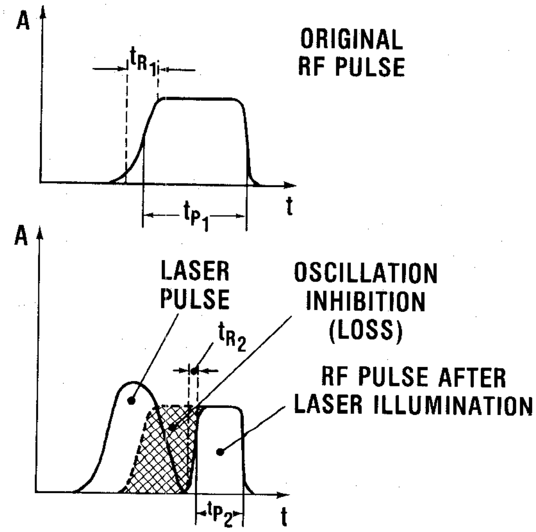

Figure 2: Time sequence for rf pulse width control.

Experimental Setup

The test vehicle chosen for the investigations is a waveguide oscillator as exhibited in figure 3A. This configuration permits easy exchange of the unpackaged Si-DD IMPATT diode while also allowing access to the diode junction for laser illumination. The lateral laser illumination of the diode junction was provided by 0.905-µm GaAs injection lasers focused by a lens system. About 750 mW of rf pulse power was attained with this open diode system. The incident laser pulse power density at the IMPATT diode projected over the area of the diode was determined by means of a dummy arrangement. The IMPATT diode was replaced by a calibrated photodetector and a power density of 2 kW/cm^2 was measured. The small size of the IMPATT diode did not permit well-defined illumination of only the junction, but resulted in the entire diode mesa being illuminated (figure 3B). Only about 1/10 of the injected laser power was effectively used. It is assumed that the p+ and n+ sections of the diode do not contribute to the generation of excess carriers, but this has not been proven yet and is under investigation.[11]

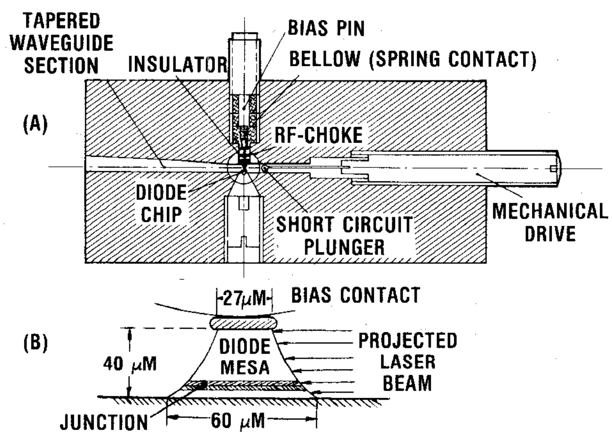

Figure 3: (A) Waveguide IMPATT oscillator structure.
(B) Laser-illuminated IMPATT diode mesa.

Experimental Results

In the course of these investigations at 70 GHz: (a) two distinct modes of operation, designated the "enhancement" and the "inhibition" modes, were observed; (b) a substantial increase of the diode current due to the laser injection during operation in the inhibition mode was observed; (c) the rf pulse width was controlled using the inhibition mode and very short pulses were obtained; (d) the intrapulse frequency chirp at low rf power was measured and reduced using the inhibition mode; and (e) AM noise measurements were carried out without illumination; measurements with optical illumination are in progress.

1. Enhancement mode. -- The enhancement mode is attained if the IMPATT diode is adjusted for threshold condition without laser illumination--i.e., if the bias current is reduced so that the oscillations just cease. The diode junction is then exposed to laser radiation to reinitiate oscillation. This mode is useful for applications where fast on-off switching or amplitude modulation of the rf pulse is required. The modulation rate can be at microwave frequencies, depending on the modulation capability of the laser. The rf pulse rise and fall time is sustained or can be improved because of the pre-bias due to the applied bias pulse.

The transition from the nonoscillating state to the oscillating state is illustrated in the upper trace of figure 4, with the laser pulse shown and positioned as in the center trace, with the IMPATT diode pulse current in the lower trace. When the laser pulse of full power was moved closer (about 4 ns) to the IMPATT current pulse, stable oscillations occurred. Also, a closer inspection of the front part of the IMPATT diode current pulse amplitude showed a small increase. This photocurrent increment indicates that only a small amount of the leading edge of the current due to photon injection is necessary to trigger the rf oscillations; the rise time is about 2.5 ns, an improvement of about 1.5 ns.

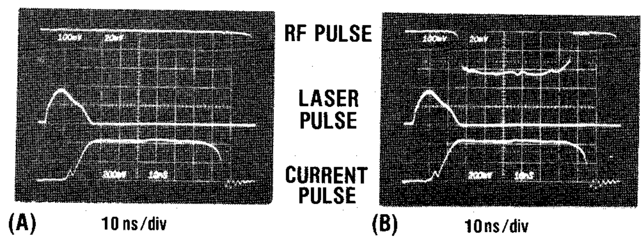

Figure 4: Enhancement mode: (A) nonoscillating case and (B) oscillating case with laser pulse properly positioned.

2. Inhibition mode. -- The inhibition mode is achieved if the IMPATT diode oscillator is adjusted for optimum operation without laser illumination and then exposed to a sufficiently high photon density so that the rf oscillations cease. In this state a considerable increase of diode pulse current due to reverse saturation or photocurrent was observed. The cessation of rf oscillations is essentially the consequence of the introduction of a resistive or dissipative component, resulting from premature avalanching ($\theta_0 < \pi/2$; see figure 1B).

The inhibition mode is demonstrated in figure 5. Part A shows an unilluminated rf pulse, while part B shows the effect of inhibiting the rear part of the pulse. In this case, the fall time of the rf pulse is

*The idea for this time sequence arose from a discussion with N. Masnari, University of Michigan, now with North Carolina State University.

considerably shorter than the laser pulse rise time. As shown in figure 5, if the front section of the rf pulse is inhibited, the "turn-on" time of the remaining part is about 2.5 ns, shorter than the laser fall time of about 8 ns. This effect can be attributed to the pre-biasing of the IMPATT diode; that is, sufficient carriers are present to assure a fast restart of oscillations. By the use of this mode, rf pulses of less than 4-ns width at 3-dB points can easily be attained (see figure 5).

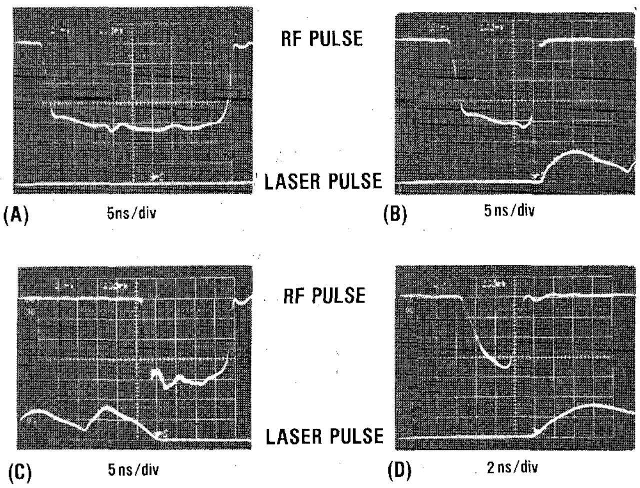

Figure 5: Inhibition mode. (A) normal rf pulse, (B) rear section inhibited, (C) front section inhibited, and (D) short pulse, rear section inhibited.

Using the inhibition mode, we were able to reduce the frequency chirp of the IMPATT diode rf pulse, as shown in figure 6. Figure 6A shows the unilluminated rf pulse and figure 6C shows the corresponding rf spectrum. By removing the last 25 ns of the rf pulse, as illustrated in figure 6B the rf spectrum in figure 6D was obtained. This spectrum is more symmetric and has more defined "zeros" of the side lobes, compared with the pulse spectrum of part C. This demonstrates that the frequency chirp has been reduced for the remaining pulse. Tentative AM-noise measurements have been made without illumination and resulted in C/N = 125 dBc/Hz, 10 kHz from the carrier. These measurements are now being extended to determine the noise characteristics of the IMPATT with and without illumination.

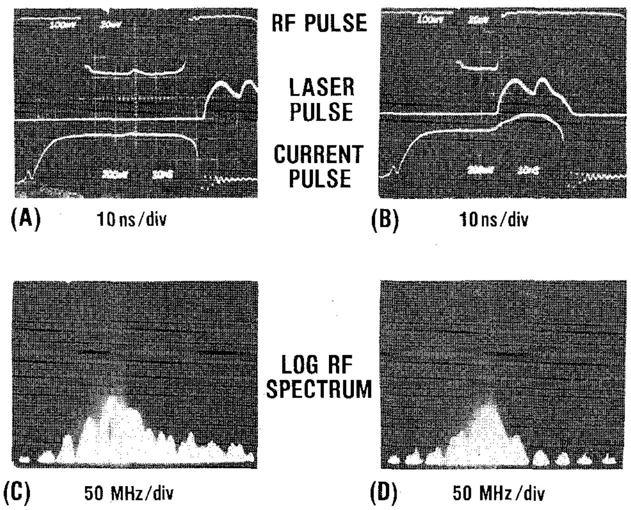

Figure 6: Chirp reduction by photon injection using inhibition mode: (A) normal rf pulse and (B) rf rear section inhibited, (C) rf spectrum corresponding to (A), and (D) rf spectrum corresponding to (B).

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