Comparison of nonlinear and nonstationary response of conventional and resonant cavity enhanced *p-i-n* photodiode

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High-power illumination of a *p-i-n* photodiode results in nonlinear operating conditions and, of course, in nonlinear electric response. This article presents an investigation and comparison of the nonlinear response of conventional and resonant cavity enhanced (RCE) *p-i-n* photodiodes constructed using a two-valley semiconductor (GaAs). The presented results are obtained through numerical simulation of the complete phenomenological model for a two-valley semiconductor in the submicron region for several bias voltages and several values of Dirac pulse optical powers. The nonlinear behavior is analyzed through carrier transit and response time. Nonstationary effects exist in two-valley semiconductors in the presence of adequate perturbation of the electric field in the absorption layer. The present investigation shows that the RCE *p-i-n* photodiode reaches the nonlinear operating regime for smaller incident optical irradiances. © *2000 American Institute of Physics.* [S0021-8979(00)09405-6]

I. INTRODUCTION

Detection of high optical radiation is a fundamental process in the characterization of high output laser pulses,[1] complex heterodyne detection schemes,[2] and some particular applications in optical communications.[3]

This article considers the resonant cavity enhanced (RCE) *p-i-n* photodiode depicted in Fig. 1(b) and matching conventional *p-i-n* photodiode depicted in Fig. 1(a). High optical power absorption in these photodetectors, causes nonlinear effects.[3–6] The nonlinear operating conditions and nonlinear electric response are predominantly caused by the space-charge effects due to the photogenerated carriers and by the change of the photodiode voltage.[3,4]

The electric field of the photogenerated carriers is calculated using the Poisson equation[4,7]

$$\frac{dK_{\mathrm{PH}}(x,t)}{dx}=\frac{q[-n_1(x,t)-n_2(x,t)+p(x,t)]}{\varepsilon_0\varepsilon_r}. \tag{1}$$

$K_{\mathrm{PH}}(x,t)$ denotes the electric field of the photogenerated carriers, $n_1(x,t)$ is the electron concentration in the central valley, $n_2(x,t)$ is the electron concentration in the satellite valleys, and $p(x,t)$ is the hole concentration. In case of low power optical absorption, the electric field of the photogenerated carriers $K_{\mathrm{PH}}(x,t)$ is significantly lower than the electric field of fixed charges in the absorption layer. Therefore, the influence of the $K_{\mathrm{PH}}(x,t)$ on the transport of the carriers in the absorption layer may be neglected and it may be assumed that transport is governed only by the electric field of the fixed charges, i.e., the response is linear. When high optical absorption is present, the electric field of the photogenerated carriers $K_{\mathrm{PH}}(x,t)$ is not negligible. In this case, the total electric field (= electric field of the fixed charges + electric field of the photogenerated carriers) in the absorption layer is nonlinear and, naturally, the carrier transport in the absorption layer is also nonlinear. The excitation level γ is defined as[7]

$$\gamma=\frac{[n(x,t=0)]_{\max}}{N}. \tag{2}$$

$[n(x,t=0)]_{\max}$ denotes the maximal concentration of photogenerated electrons (holes) in the absorption layer at the initial moment and N denotes the concentration of the donor impurities in the absorption layer. For the conventional *p-i-n* photodiode illuminated from the *p* side $x=0$,[5] and in case of the RCE *p-i-n* photodiode, also illuminated from the *p* side, x is determined using the parameters of the resonant cavity, i.e., using quantum efficiency.[7] (Details of the absorption process in considered types of the *p-i-n* photodiodes are explained in Refs. 5 and 7.) The excitation level γ is used to describe the transport conditions explained above. Namely, when γ is less than unity linear operating conditions are assumed. When γ is greater than unity the field of the photogenerated carriers must be taken into account, hence the response must be treated as nonlinear.

In the model, the *p-i-n* photodiode is treated with ''time-dependent'' (photodiode/bias) voltage.[5,7] In the linear operating regime, change of the voltage of *p-i-n* photodiode is practically negligible,[5,7] but owing to the significant value of the photocurrent, the change in the *p-i-n* photodiode voltage in the case of higher optical absorption power is not negligible.[3,4] The change of the voltage of the *p-i-n* photodiode affects the total electric field in the absorption layer, and reinforces the already existed nonlinear transport conditions in the absorption layer.[4]

The applied model also takes into account intervalley electron transfer. According to the assumptions, which are used in the complete phenomenological model, the intervalley electron transfer is governed only by the electric field in the absorption layer.[5,7] Therefore, the nonstationary effects

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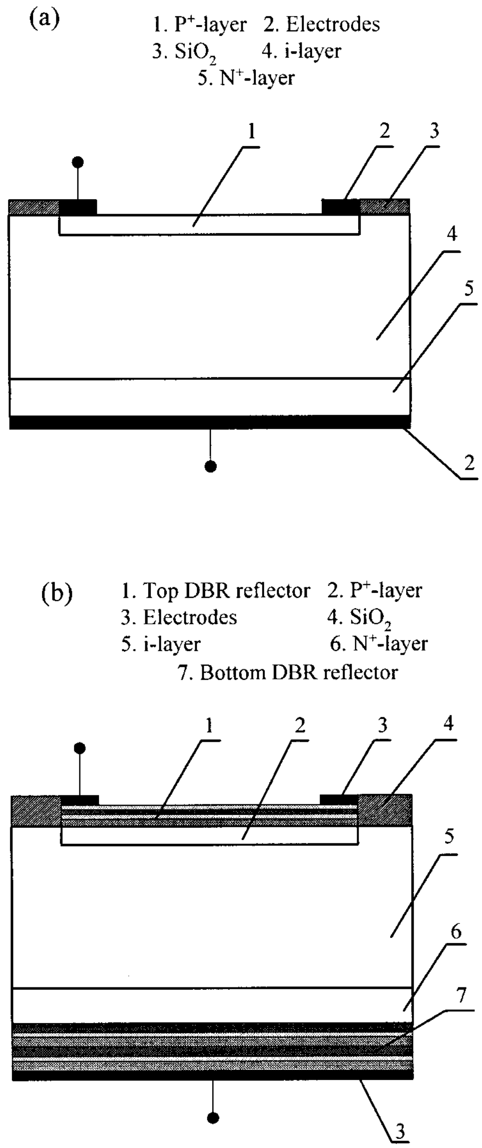


FIG. 1. Structure of the considered (a) conventional and (b) RCE *p-i-n* photodiode.

caused by the intervalley electron transfer, i.e., change of the electric field, may also be present and induce nonstationary response.

The interference of all the effects described above and the comparison of those effects in the case of the conventional and the RCE *p-i-n* photodiode are investigated and presented in this article.

II. NONLINEAR RESPONSE CHARACTERIZATION

The photodiode is exposed action of Dirac pulse excitation. Whereas photodiode considered is made of GaAs (two-valley semiconductor), wavelength of incident radiation is 0.8 μm. We consider the response of the *p-i-n* photodiode in nonlinear operating regime. Therefore, it is not possible to use bandwidth for the characterization of response. The response is presented and discussed through the carrier transit times and the response time, because these parameters are valid for the characterization of the response independent of the operating regime.

The electron transit time is defined as

$$\tau_n = \frac{\int_0^\infty t j_n(d,t)\,dt}{\int_0^\infty j_n(d,t)\,dt} \tag{3}$$

and the hole transit time is defined as

$$\tau_p = \frac{\int_0^\infty t j_p(0,t)\,dt}{\int_0^\infty j_p(0,t)\,dt}. \tag{4}$$

$j_n(d,t)$ is the total conduction current of the electrons (electrons in central and satellite valleys) at the position $x=d$, where electrons are leaving the i layer and $j_p(0,t)$ is the conduction current of the holes at the position $x=0$, where the holes leave the absorption layer.[5,7]

The response time is

$$T_R = \frac{\int_0^\infty t I(t)\,dt}{\int_0^\infty I(t)\,dt}. \tag{5}$$

$I(t)$ denotes the total current of the *p-i-n* photodiode.[4,5,7]

Both the conventional and the RCE *p-i-n* photodiode are considered to have a submicron thickness absorption layer ($d=0.6\,\mu$m; Fig. 1). The quoted thickness of the absorption layer corresponds to the maximum quantum efficiency of the considered RCE *p-i-n* photodiode in the submicron region.[7] Although the conventional *p-i-n* photodiode is not applicable with the submicron thickness of i layer, it is considered because of the intent to compare these two types of *p-i-n* photodiodes and investigate possible advantages and/or disadvantages of the resonant cavity on the speed and sensitivity of the *p-i-n* photodiode in nonlinear operating conditions.

III. NUMERICAL TECHNIQUES

The results are obtained through a numerical simulation of the complete phenomenological model for a two-valley semiconductor. This model, consisting of 18 equations, is explained in detail in Refs. 5 and 7. The model is solved by the method of finite differences and simulations are carried out respecting all the necessary conditions for the stability of the numerical algorithm.[5,7]

Certain difficulties are present in numerical simulations of the nonlinear response. Namely, in the initial moment the photogenerated carriers have very strong diffusion tendency. The electric field in the absorption layer cannot disable that current flow and therefore we have a leakage current which is a parasitic component in the total current flow. In the case of low optical absorption, the leakage current becomes significant only when bias voltage is very small. But, when we deal with high absorption, the leakage current is not negligible for the broad list of operating parameters. We adopted criteria that obtained results are valid only if the leakage current is less than 10% of the total electron/hole current. The influence of the leakage current is particularly prominent in the case of the RCE *p-i-n* photodiode, due to the very complex optical generation in the i layer.

IV. RESULTS AND DISCUSSION

The nonlinear response is analyzed for a relatively broad range of excitation levels ($0<\gamma\leqslant 100$). In the beginning, it

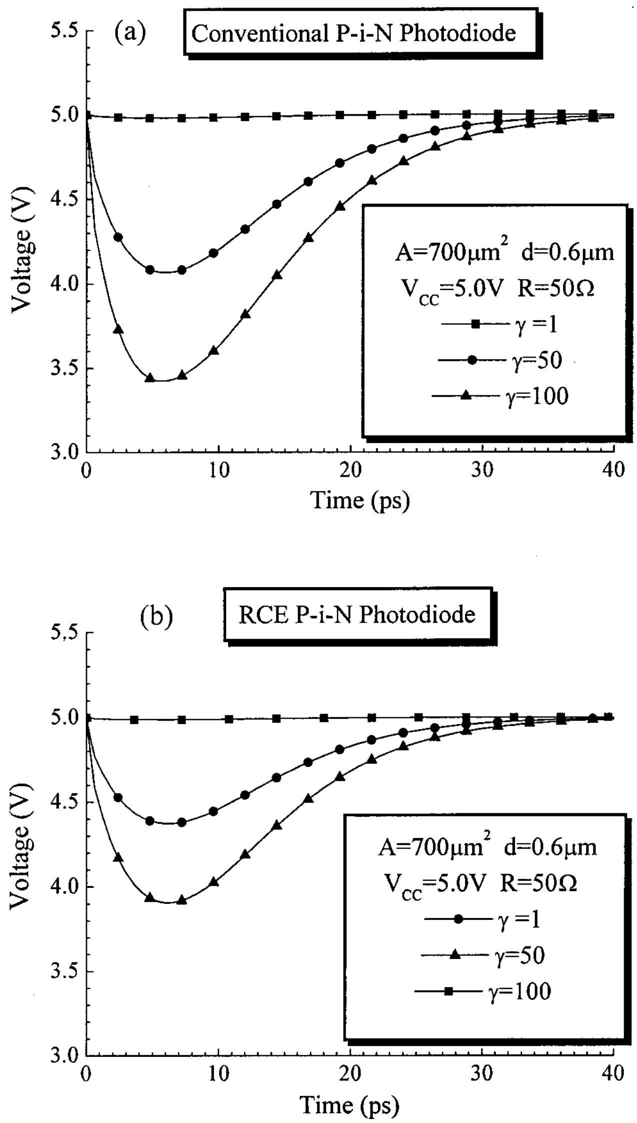


FIG. 2. Time dependence of the (a) conventional and (b) RCE *p-i-n* photodiode voltages in case of three different excitation levels ($\gamma=1$, $\gamma=50$, and $\gamma=100$), active area $A=700\ \mu\text{m}^2$, absorption layer thickness $d=0.6\ \mu\text{m}$, bias voltage $V_{CC}=5$ V, and load resistance $R=50\ \Omega$.

must be emphasized that the same excitation levels, i.e., optical generations, for conventional and RCE *p-i-n* photodiode are achieved through different incident irradiances. Owing to the interference effects, in the case of the RCE *p-i-n* photodiode, the same excitation level is achieved with significantly lower irradiances than in case of the conventional *p-i-n* photodiode. Therefore, when dealing with the RCE *p-i-n* photodiode, the nonlinear effects have to be taken into account at lower incident optical powers than in the case of the conventional *p-i-n* photodiode. It is the main reason why we consider nonlinearity to be an important effect in the application of the RCE *p-i-n* photodiode.

Figure 2(a) depicts time dependence of the conventional *p-i-n* photodiode voltage in the case of the different excitation levels. The considered excitation levels are $\gamma=1$, $\gamma=50$, and $\gamma=100$. The active area of the photodiode is $A=700\ \mu\text{m}^2$, bias voltage is $V_{CC}=5$ V, thickness of the absorption layer is $d=0.6\ \mu\text{m}$, and load resistance is $R=50\ \Omega$. Figure 2(b) depicts time dependence of the voltage in the case of the RCE *p-i-n* photodiode for the same excitation levels, bias voltage, and photodiode parameters. The significant decreasing of the voltage with the increasing of the excitation level is noticeable. Regardless on the same excitation levels, the minimums of the voltage of the conventional *p-i-n* photodiode are lower when compared with the RCE *p-i-n* photodiode, which means that the perturbation of the electric field in the absorption layer is lower in case of the RCE *p-i-n* photodiode than in the case of the conventional *p-i-n* photodiode. The described situation is caused for two different reasons. The first is, as it is mentioned above, the same excitation levels are achieved with the different incident optical radiation. Lower optical radiation in case of the RCE *p-i-n* photodiode causes the total concentration of photogenerated carriers in the absorption layer to be lower when compared to the conventional *p-i-n* photodiode. In addition, the spatial distribution of photogenerated carriers in the absorption layer also has a significant influence. The separate contribution of the photogenerated electrons and holes to the space-charge electric field is larger in the case of the conventional *p-i-n* photodiode than in the case of the RCE *p-i-n* photodiode. As the consequence, for the same parasitic RC constant, the displacement current of the RCE *p-i-n* photodiode has lesser influence on the total current than in the case of the conventional *p-i-n* photodiode.

Figure 3(a) represents the dependence of the response time and electron/hole transit time of the excitation level for the conventional *p-i-n* photodiode. The applied bias voltages are $V_{CC}=2$ V and $V_{CC}=5$ V, the active area is $A=700\ \mu\text{m}^2$, thickness of the absorption layer is $d=0.6\ \mu\text{m}$, and load resistance is $R=50\ \Omega$. Figure 3(b) represents the same dependencies for the RCE *p-i-n* photodiode, for the identical photodiode parameters and operating conditions as in the case of the conventional *p-i-n* photodiode. We shall first consider the represented dependencies individually and then carry out the comparison. When the excitation level is low (the influence of space-charge effects is negligible; linear case), the electric field in the *i* layer provides that electrons are predominantly localized in satellite valleys and unsaturated for both values of the applied bias voltage and holes are saturated. But, when the applied bias voltage is $V_{CC}=2$ V, holes are close to the edge of the saturation, while in case of the applied bias voltage $V_{CC}=5$ V, holes are deeply in saturation. As the excitation level increases, the total electric field in the absorption layer decreases owing to the space-charge effects caused by photogenerated carriers. When the applied bias voltage is $V_{CC}=2$ V, present decreasing of the total electric field is enough to move holes in the unsaturated region. In that region, the velocity of holes is dependent on the electric field and therefore increasing of the transit time of holes versus the excitation level is noticeable. When the applied bias voltage is $V_{CC}=5$ V, the transit time of holes is constant up to approximately $\gamma=90$. For higher excitation levels, slight increasing of the transit time of holes is present, owing to enough decreasing (for this bias voltage) of the total electric field. When the applied bias voltage is $V_{CC}=2$ V, the total electric field (in the linear case) is about 33 kV/cm which is close to the region of values of the elec-

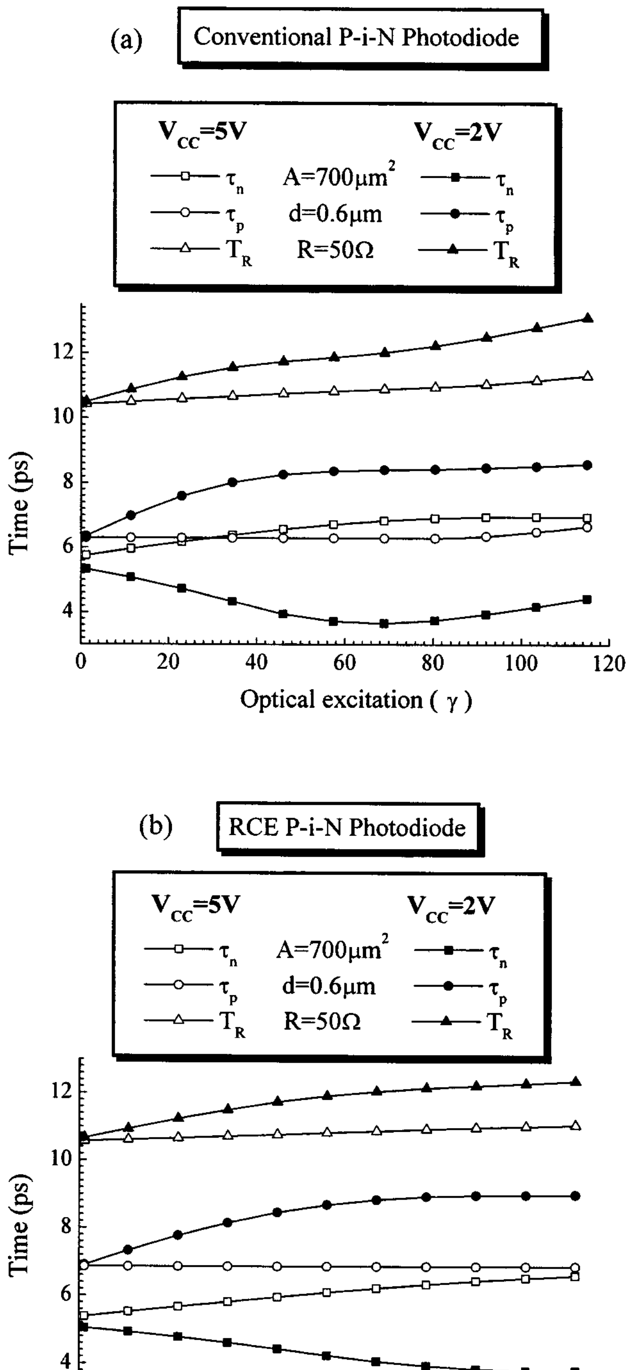


FIG. 3. Response time and electron/hole transit time vs the excitation level for the (a) conventional and (b) RCE *p-i-n* photodiode in the case of two different bias voltages ($V_{CC}=2$ V and $V_{CC}=5$ V), active area $A=700\ \mu\mathrm{m}^2$, thickness of the *i* layer $d=0.6\ \mu$m, and load resistance $R=50\ \Omega$.

tric field where the electron intervalley transfer is significant.[5,7] Therefore, as the excitation level increases, the total electric field decreases and electrons are scattered from the satellite valleys into the central valley. Their velocity in the central valley is significantly higher, and therefore, the electron transit time decreases. When the excitation level corresponds to the minimum of the transit time of electrons, we may assume that electrons are predominantly localized in the central valley and unsaturated. Therefore, with the further increasing of the excitation level (i.e., decreasing of the total electric field), the transit time of electrons again increases due to the decreasing of the velocity of electrons. When the applied bias voltage is $V_{CC}=5$ V, all electrons are scattered in the satellite valleys and increase of the excitation level (i.e., decrease of the total electric field) will always cause an increase in the electron transit time. The response time of the device is determined by the slower carriers. Therefore, the behavior of the response time is a consequence of a complex mechanism of electron and hole transport through the absorption layer, but significantly longer because the transit time includes the influence of the parasitic RC constant on the speed of the photodiode. The influence of RC constant is dominant for the considered parameters and operating conditions of the photodiode.

The perturbation of the total electric field in the absorption layer of the RCE *p-i-n* photodiode, as described above, is lesser than in case of the conventional *p-i-n* photodiode. This fact affects the behavior of the considered times versus the excitation level. When the excitation level is low, the situation in the absorption layer is very similar to the conventional *p-i-n* photodiode. Holes are saturated and electrons are predominantly localized in the satellite valleys. When the excitation level increases, in case of the applied bias voltage $V_{CC}=2$ V, holes became unsaturated and naturally the transit time of holes increases. When the applied bias voltage is $V_{CC}=5$ V, owing to the decreased influence of perturbation, holes are in saturation for all excitation levels and the transit time of holes is constant. For $V_{CC}=2$ V, the electron transit time decreases for all excitation levels. The electric field values provide electron intervalley transfer, but the electric field does not reach values that provide for all electrons to be in central valley as in the case of the conventional *p-i-n* photodiode. Therefore, the increasing part is missing. When the bias voltage is $V_{CC}=5$ V, the total electric field has values for which all electrons are localized in satellite valleys. They are not in the saturation and the transit time is permanently increasing. As in case of the conventional *p-i-n* photodiode, the response time is predominantly determined with the RC constant and has larger values.

An explanation of the Fig. 3 discussed above is confirmed by the following figures. Figures 4(a) and 4(b) depict the dependence of the total electric field on the time and on the spatial position in the absorption layer of the conventional and RCE *p-i-n* photodiode, respectively, for the applied bias voltage $V_{CC}=5$ V, active area $A=700\ \mu\mathrm{m}^2$, *i* layer thickness $d=0.6\ \mu$m, load resistance $R=50\ \Omega$, and excitation level $\gamma=50$. It is noticeable that the perturbation of the total electric field of the conventional *p-i-n* photodiode is larger when compared to the RCE *p-i-n* photodiode. In both cases, values of the electric field do not reach the region of an electron intervalley transfer or the region where the holes are unsaturated. As discussed above, holes are in saturation and electrons are localized in the satellite valleys for the quoted parameters.

Figures 5(a) and 5(b) represent electric field versus time and spatial position in *i* layer for the conventional and RCE

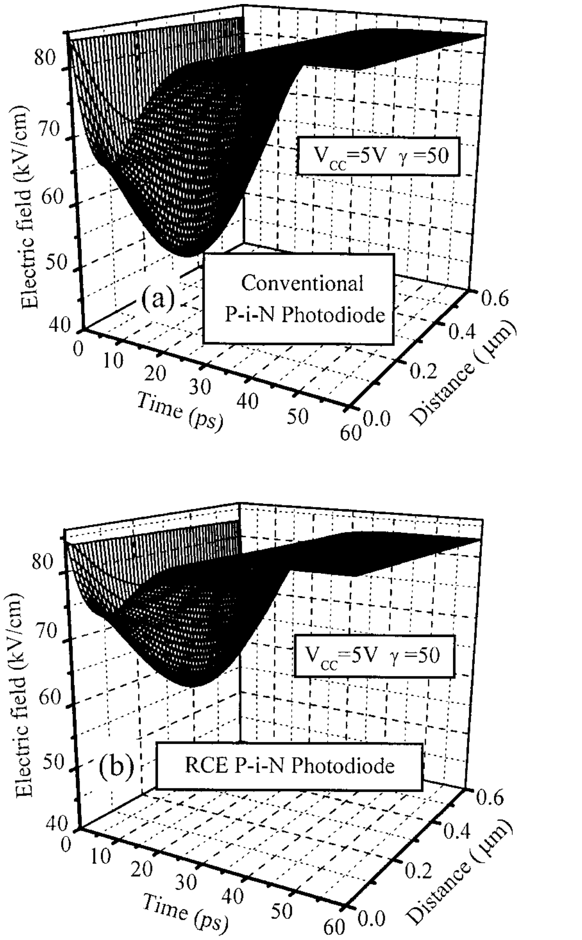


FIG. 4. 3D dependence of the total electric field of the time and the spatial position in the *i* layer of the (a) conventional and (b) RCE *p-i-n* photodiode for bias voltage $V_{CC}=5$ V, excitation level $\gamma=50$, active area $A=700\ \mu\text{m}^2$, absorption layer thickness $d=0.6\ \mu$m, and load resistance $R=50\ \Omega$.

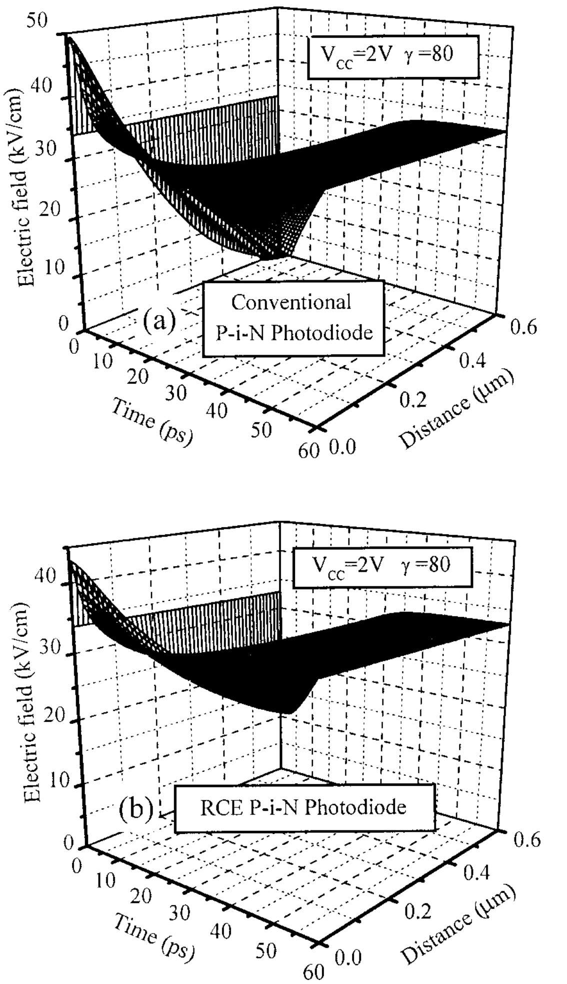
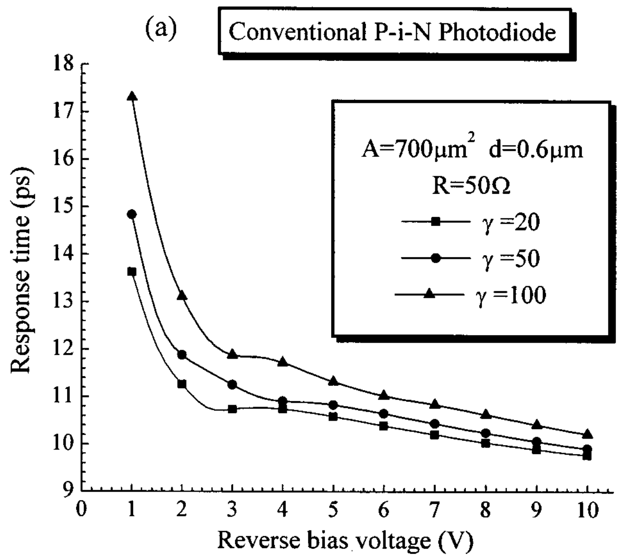


FIG. 5. Same as Fig. 4 only for bias voltage $V_{CC}=2$ V and excitation level $\gamma=80$.

p-i-n photodiode, respectively. The reverse bias voltage is $V_{CC}=2$ V, active area is $A=700\ \mu\text{m}^2$, absorption layer thickness $d=0.6\ \mu$m, load resistance $R=50\ \Omega$, and excitation level $\gamma=80$. In both situations, values of the electric field provide unsaturated holes ($K<33$ kV/cm). In the case of the RCE *p-i-n* photodiode, the electric field has values in the region where electron intervalley transfer is present,[5,7] but does not have values lesser than 10 kV/cm for which electrons are predominantly localized in the central valley. In contrast, the electric field of the conventional *p-i-n* photodiode reaches values close to zero, for which electrons are indeed localized in the central valley.

Figures 6(a) and 6(b) depict the dependence of the response time of the applied reverse bias voltage in the case of the conventional and RCE *p-i-n* photodiode, respectively. The dependence is investigated for three excitation levels $\gamma=20$, $\gamma=50$, and $\gamma=100$, active area $A=700\ \mu\text{m}^2$, thickness of the *i* layer $d=0.6\ \mu$m, load resistance $R=50\ \Omega$, and bias voltages $0\ \text{V}<V_{CC}\leqslant 10$ V. It is noticeable that in both considered cases that the response times decrease with the increase of the bias voltage. This is expected behavior because as the bias voltage increases, the total electric field also increases and the velocity of carriers becomes higher. If the excitation level is constant, all curves have, generally speaking, three segments with different slopes. In the region where the reverse bias voltage is roughly less than 2 V, in both cases, curves have great slopes. Electrons are localized in the central valley and holes are unsaturated, due to the values of the total electric field in the absorption layer. Being slower than electrons, holes determine the speed of the device, i.e., the response time. For the bias voltages greater than roughly 5 V, all curves have significantly lower slopes. A larger values of the total electric field in the *i* layer causes the localization of electrons in the satellite valleys. Therefore, they become the predominant limiting factor of the speed of the device and naturally determine the slope of the curve of the response time versus the applied bias voltage. The segment of the curve between two segments mentioned above corresponds to the electron intervalley transfer.[7] Values of the total electric field in the *i* layer correspond to the region where the electron intervalley transfer is present. In fact, in that region the change of the limiting factor is made and the slope is different from the other two slopes but the holes are still the limiting factor of the speed. In both cases, it is noticeable that values of the bias voltage corresponding to the beginning of the electron intervalley transfer increase as the excitation level increases and that the response time is longer



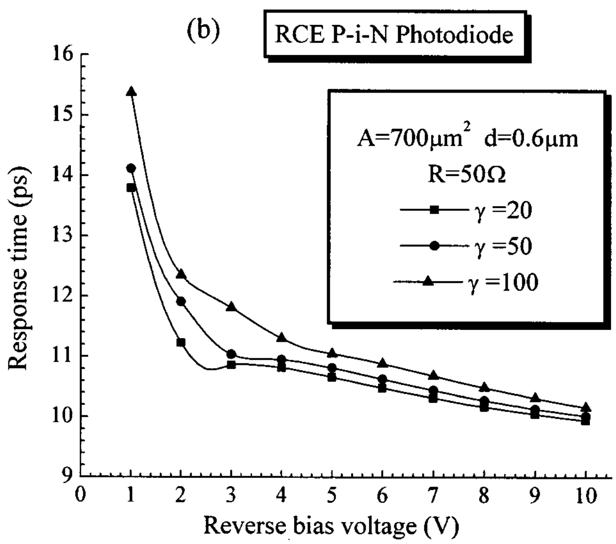


FIG. 6. Time response vs the bias voltage of the photodiode for the (a) conventional and (b) RCE *p-i-n* photodiode in the case of three different excitation levels ($\gamma=20$, $\gamma=50$, and $\gamma=100$), active area $A=700\ \mu\text{m}^2$, absorption layer thickness $d=0.6\ \mu\text{m}$, and load resistance $R=50\ \Omega$.

when the excitation level is higher, for the same bias voltage. These facts were predictable because high optical absorption causes larger perturbation of the electric field in the absorption layer, i.e., the total electric field in the absorption layer is lesser when the optical absorption is higher. The reverse bias voltage is constant.

The linear responses of the conventional and the RCE *p-i-n* photodiode are comprehensively presented in Refs. 5, 7, and 8. In the linear operating regime, the RCE *p-i-n* photodiode has significant advantages. Applicable values of the quantum efficiency are achieved using a submicron thickness of the absorption layer where *p-i-n* photodiode has the largest values of the bandwidth. High speed and high quantum efficiency are accomplished simultaneously, which is an obvious advantage of the RCE *p-i-n* photodiode when compared to the conventional *p-i-n* photodiode. These characteristics make the RCE *p-i-n* photodiode, a superior device today in optoelectronic circuits and ultralong band optical communications.[8] In the case of nonlinear operating regime, the same conclusion cannot be derived straightforward from the observation above. The RCE *p-i-n* photodiode reaches the nonlinear operating regime with considerably lesser incident irradiances than the conventional *p-i-n* photodiode. This means that in applications where the conventional *p-i-n* photodiode operates in the linear regime, the RCE *p-i-n* photodiode may operate in the nonlinear regime. It is noticeable that any significant difference in the speed, i.e., the response time, of the considered types of the *p-i-n* photodiodes is not present. The response time shows similar dependencies on the excitation level and the applied reverse bias voltage.

V. CONCLUSIONS

The presented results lead to the following conclusions:

The RCE *p-i-n* photodiode reaches the nonlinear operating regime for considerably lower incident optical powers compared to the conventional *p-i-n* photodiode, owing to the resonant cavity presence. Depending on the concrete application, this feature may be of great advantage or great disadvantage. It is necessary to emphasize that the nonlinear effects in the case of the RCE *p-i-n* photodiode have to be taken into account at less incident irradiances than in the case of the conventional *p-i-n* photodiode.

The response time in both cases is dependent on the excitation level, i.e., incident irradiances. The parasitic RC constant has predominant influence on the response time. Any significant difference in the response times of the conventional and RCE *p-i-n* photodiode is not noticeable. The dependence of the hole transit time on the excitation level is practically the same for both applied bias voltages in case of the conventional and RCE *p-i-n* photodiode. But, the behavior of the electron transit time versus the excitation level is significantly dependent on the applied bias voltage. Namely, when the bias voltage is $V_{CC}=2$ V, the transit time decreases as the excitation level increases, for both considered types of the *p-i-n* photodiodes. In case of the conventional *p-i-n* photodiode, the transit time has a minimum, i.e., it is possible to select the excitation level which provides the maximum speed of electrons in the device. When the applied bias voltage is $V_{CC}=5$ V, the electron transit time is increasing curve versus the excitation level.

The nonstationary effects which are the consequence of electron intervalley transfer are present and have certain influence on the considered times. Due to larger perturbation of the total electric field in the absorption layer, nonstationary effects are more prominent in case of the conventional *p-i-n* photodiode. This is especially noticeable in the case of electron transit time. The nonstationary effects have less influence on the response time.

The response time is dependent of the applied reverse bias voltage. As the bias voltage increases, the response time decreases, i.e., the speed of the device increases. For the range of the bias voltage, roughly $2\ \text{V} \leqslant V_{CC} \leqslant 5\ \text{V}$, the influence of the nonstationary effects is noticeable for all considered excitation levels.

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