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Influence of electrode parameters on the performance of optically controlled MESFETs

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Abstract

The effects of electrode spacing on the optical response of illuminated MESFETs are analyzed. The analysis targets various optical performance factors including terminal photocurrent peak value, peak-time and discharge time. Whereas photocurrent peak value increases nonlinearly with electrode spacing, it was found that increasing the electrode spacing has a profound effect on the ability of the device to flush-out the optically generated carriers and hence more output delays are generated. A figure-of-merit has been defined to quantify the overall spacing effects. The simulation results show that optimum electrode spacing can be achieved.
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Keywords: Optoelectronics; FDTD; Illumination effects

1. Introduction

One of the most astonishing developments in modern technology has been the rapid advance in ultrafast optics and its applications in telecommunications. As the capacity of information increases, the ability to handle information has to increase as well, creating a demand for high-speed optoelectronic technology. Optoelectronics has a rapidly growing range of applications that includes optical communications, optical data storage and optical sensing. It is mainly concerned with the interaction of light with active devices that establishes the interface between electronics and optics. Consequently, the ability to control the intrinsic properties of active devices using optical signals prompted a huge research interest. Driven by the ever-increasing demand on telecommunication services and facilities, intensive research has been focused on a better utilization of the high bit rates provided by optical links. Optically controlled active devices (OCAD) have the ability to transform light modulating signals into changes in the active device characteristics, bridging the gap between electronic and optical control with many attractive features. For example, extra electronic circuits for optical signal detection are not needed and good electrical isolation is achieved. Also, extra circuit parasitics that limit the speed of the response are eliminated. Research papers in OCAD modeling and characterization under illuminated conditions range from simplified theoretical treatment and equivalent circuit models of the effects on small and large-signal characteristics [1–3], to more elaborate analytical and physical models [4–8]. A good review of the early work on OCADs can be found in Ref. [9].

In the context of high frequency microwave and millimeter wave operation and short gate length device, the modeling problem of OCADs extends beyond the applicability of the aforementioned approaches [9–11]. Physical modeling provides great advantages to research and design engineers by allowing the researcher to investigate the effect of a large number of device parameters and nonlinear operating conditions including device dimensions, material, inhomogeneous structures, internal effects such as scattering and relaxation, external effects such as bias and temperature, and multidimensional analysis. Furthermore, this type of analysis allows for coupling of different contributing physical models to form a global physical analysis technique.

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In this paper, a detailed analysis of the effects of electrode spacing on the optical response of illuminated MESFETs is presented. The analysis targets various optical performance factors including terminal photocurrent peak value, peak-time and discharge time. A figure-of-merit (FoM) is defined to quantify the overall spacing effects on optical efficiency.

2. Device model under illumination

In order to describe the illumination effects on the behavior of the active device, accurate modeling of the carrier transport as well as the illumination interaction mechanisms has to be sought. The carriers in sub-micrometer gate-length devices transport under non-isothermal and non-equilibrium conditions. As a result, appropriate account for the relationship between carrier transport parameters and carrier energy has to be made. Also, the spatial and temporal variations in the carrier momentum cannot be neglected. A transport model based on Boltzmann's transport equations, which accounts for these variations, is employed. On the other hand, illumination effects inside the active device are appropriately included by adequate representation of carrier photo-generation.

2.1. Active device model

Because the MESFET is intended for high-frequency operations, simplified models based on the drift–diffusion equations and local models are not adequate. These models assume quasi-static and equilibrium conditions. The Boltzmann's transport equations, on the other hand, provide a time-dependent self-consistent solution for carrier density, carrier energy and carrier momentum, and take care of sub-picosecond non-equilibrium transport. They are given by [10]

$$\frac{\partial n}{\partial t} + \nabla(nv) = 0 \tag{1}$$

$$\frac{\partial e}{\partial t} + v\nabla e + \frac{1}{n}\nabla(nk_{\mathrm{B}}Tv) = -q(E)v - \frac{e - e_{\mathrm{o}}}{\tau_{\mathrm{e}}} \tag{2}$$

$$\frac{\partial(mv_{x,y})}{\partial t} + v\nabla(mv_{x,y}) + \frac{q}{n}\frac{\partial}{\partial x, y}(nk_{\mathrm{B}}T) = -qE_{x,y} - \frac{v_{x,y}}{\tau_{\mathrm{m}}} \tag{3}$$

where n is the electron density, v is the electron velocity, e is the electron energy, E is the electric field intensity, m is the electron effective mass, T is temperature and τ_{e} and τ_{m} are the energy and momentum relaxation times, respectively.

2.2. Photogeneration model

The process of carrier generation due to the absorption of light and the subsequent recombination processes alter the distribution of carriers inside the device. To account for this effect, the carrier conservation equation, Eq. (1), is amended with generation and recombination rates as

$$\frac{\partial n}{\partial t} + \nabla(nv) = G - R \tag{4}$$

The generation rate, G, is a function of optical intensity, material absorption coefficient and spatial distribution, and is given by

$$G = \phi\alpha\,\mathrm{e}^{-\alpha y} \tag{5}$$

where α is the optical absorption coefficient of the material. In Eq. (5), ϕ represents the profile of the incident beam in the transverse direction modulated by a time-domain pulse such that

$$\phi(x, t) = \phi_{\mathrm{o}}\,\mathrm{e}^{-(x-x_{\mathrm{o}})^2/\sigma_x^2}\,\mathrm{e}^{-(t-t_{\mathrm{o}})^2/\sigma_t^2} \tag{6}$$

where ϕ_{o} is the peak incident power. A number of recombination processes can take place inside the active device such as the Shockley–Read–Hall process and the Auger recombination process [12]. All of these processes contribute to the recombination rate, R.

The coupling procedure between the two models can be understood by inspecting the physical operations that take place inside the device. The absorbed light creates a disturbance in the carrier distribution inside the device, which, in turn, results in a change in the current densities. The moving free charges in the non-illuminated and illuminated cases behave as sources of electric fields which alter the carrier velocity and energy. In this fashion, energy exchange between the device and the optical input is established. It should be mentioned here that under non-equilibrium conditions, photo-induced anharmonic distortions in the carrier energy can take place. High-intensity illuminations may create photo-induced non-centrosymmetry within the material giving rise to the possibility of second-order nonlinear effects. In such situations, the electrical properties of the device will be more appropriately described by third rank polar tensors. These effects significantly contribute to the previously described kinetics [13].

3. Results and analysis

The model equations are solved numerically using the finite-difference time-domain (FDTD) technique. The FDTD formulation is complemented with the definition of appropriate boundary conditions around the simulated structure. The dielectric constant of each region of the structure is incorporated in the formulation of Poisson's equation that is solved self-consistently with the device model equations. This procedure is marched in time until transient as well as steady-state solutions are achieved. Details of the formulation and setup of the numerical scheme can be found in Ref. [10]. Fig. 1 shows the MESFET structure under study. The optical characteristics of this structure were extensively studied in a previous publication [9]. Also, Table 1 gives the device parameters and operating conditions used in this particular study.

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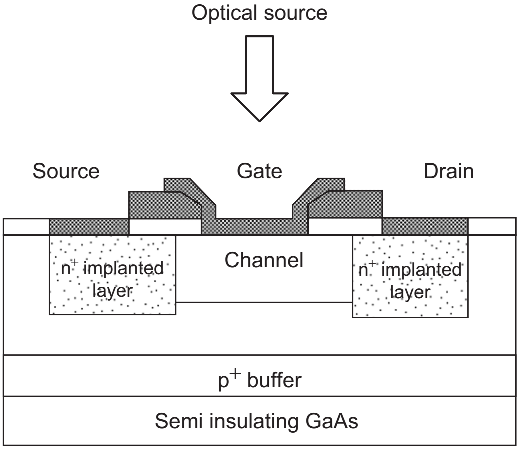

Fig. 1. MESFET structure used in the analysis.

Table 1
Device parameters used in the simulation

Drain and source contacts (μm)	0.5
Gate length (μm)	0.2
Active layer thickness (μm)	0.1
Active layer doping (cm^{-3})	2×10^{17}
Substrate doping (cm^{-3})	1×10^{14}
Peak optical flux density ($cm^{-2}\,s^{-1}$)	2×10^{21}
Gate–source bias (V)	0.0
Drain–source bias (V)	2.0
Absorption coefficient (cm^{-1})	1×10^{4}

As given, the device is operated in the saturation region such that amplification of the optical response is attained. The current investigations are concerned with the optimum design of optically controlled MESFET structures such that considerable improvement in photoelectric conversion efficiency is achieved without compromising the electrical characteristics. As indicated earlier, illumination induces a considerable disturbance in the steady-state carrier distribution inside the device through the carrier generation process and the subsequent high-field transport. The region of high carrier concentration extends well into the substrate as shown in Fig. 2. The applied optical Gaussian pulse has a 10-ps waist and a spot size of 25 μm. The time-domain simulations of the device response show the significant effect of electrode spacing, specifically, the drain–gate separation, as shown in Fig. 3. On the other hand, the effects of source–gate spacing are less significant (Fig. 4). As illustrated in Fig. 5, the peak value is a strong function of the drain–gate separation. It increases sharply as the separation is increased from 0.3 to 0.8 μm because more MESFET surface is exposed to illumination resulting in more carriers being generated and transported to the drain by the high field region. However, as the drain–gate separation is increased further and up to 1.4 μm, the increase in photocurrent peak value slows down. This behavior is due to the long journey that carriers have to travel to the drain contact. Chances of recombination become greater and less current is expected. The time delay

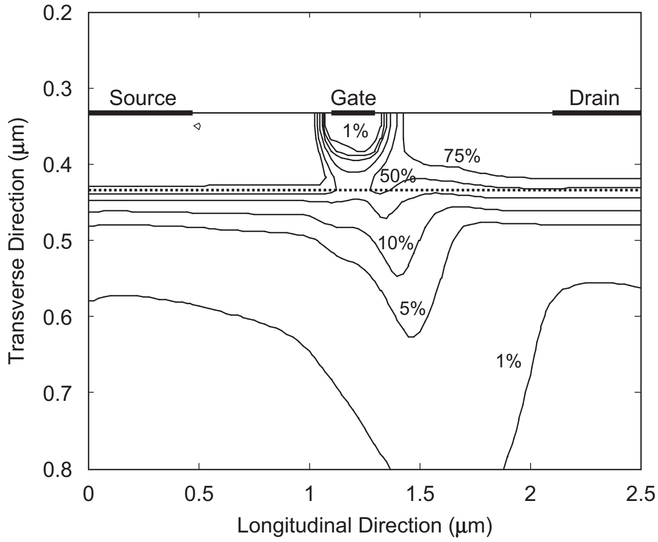

Fig. 2. Electron concentration in an illuminated device.

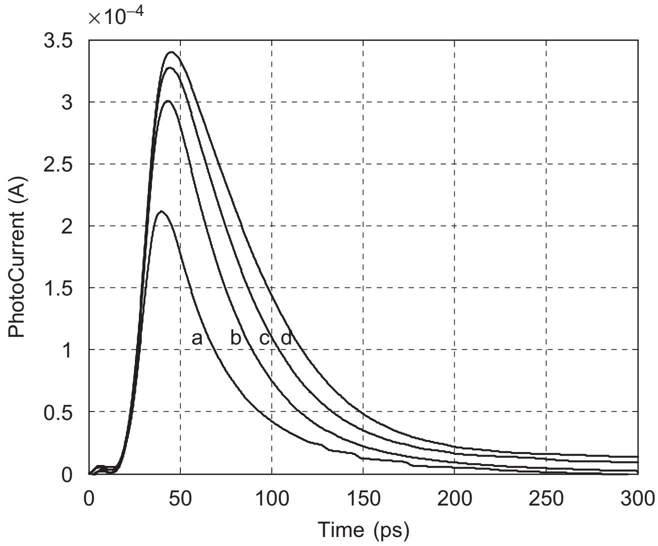

Fig. 3. Photocurrent generated in response to a 20-ps light pulse. The characteristics of the output electronic pulse are a strong function of drain–gate separation: (a) 0.5 μm, (b) 0.8 μm, (c) 1.1 μm and (d) 1.4 μm.

of the peak current as a function of drain–gate separation is shown in Fig. 6. The peak of the input optical pulse occurs at $t = 30$ ps. The time delay in the generated electrical signal represents the charging time of the structure. It is fair to say that increasing the separation from 0.3 up to 1.4 μm does not affect the peak time significantly. More crucial is the discharge time of the device. Fig. 7 shows that increasing the electrode spacing has a profound effect on the ability of the device to flush-out the optically generated carriers. The resistance per unit length of the device increases as the distance between the gate and drain increases. On the other hand, the junction capacitance at the gate increases as more carriers are generated and the reverse bias at the gate is lowered. As a first approximation, the discharge time of the device

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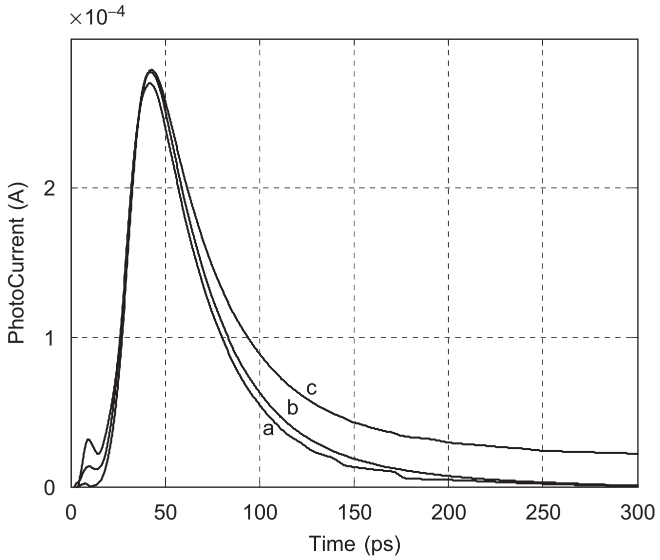

Fig. 4. The effect of source–gate separation (a) 0.3 μm, (b) 0.6 μm and (c) 1.0 μm, on the generated photocurrent with fixed drain–gate separation.

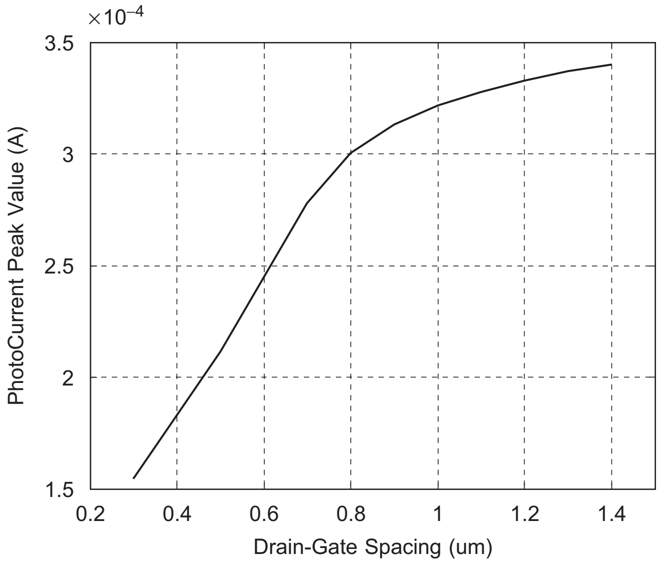

Fig. 5. The effect of drain–gate separation on device peak current.

increases linearly with electrode spacing, as shown in Fig. 7.

To quantify the trade-off between conversion efficiency and device switching characteristics, it is important to sum-up these effects in a single representative quantity. A FoM can be defined as

$$\text{FoM} = \frac{\text{Peak current value}}{\text{Discharge time}} \tag{7}$$

To maintain the highest possible level of optical-to-electrical energy conversion without significantly limiting the device switching speed, the FoM has to be maximized. In Fig. 8, the FoM is plotted versus drain–gate separation. The plot is normalized by the maximum value. It is clear

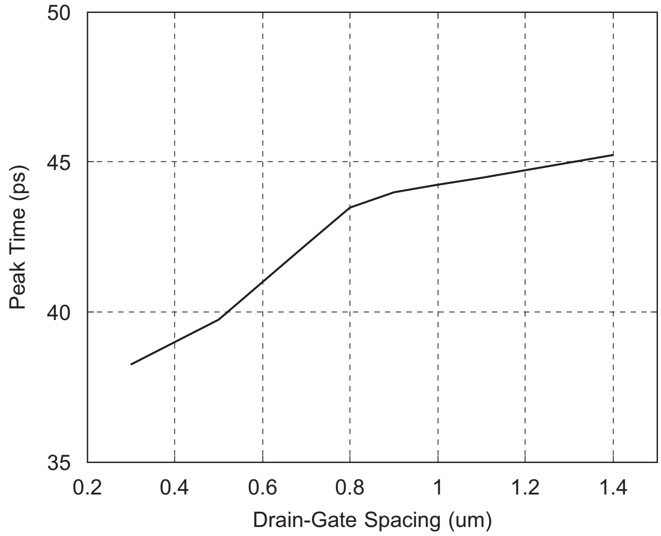

Fig. 6. The effect of drain–gate separation on peak time.

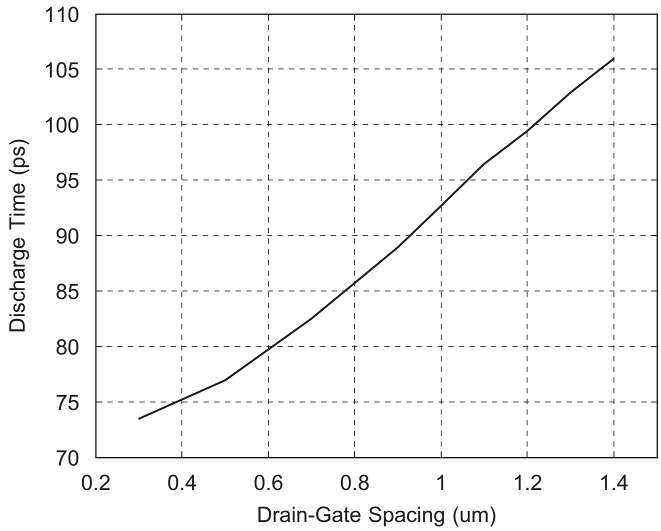

Fig. 7. The effect of drain–gate separation on device discharge time.

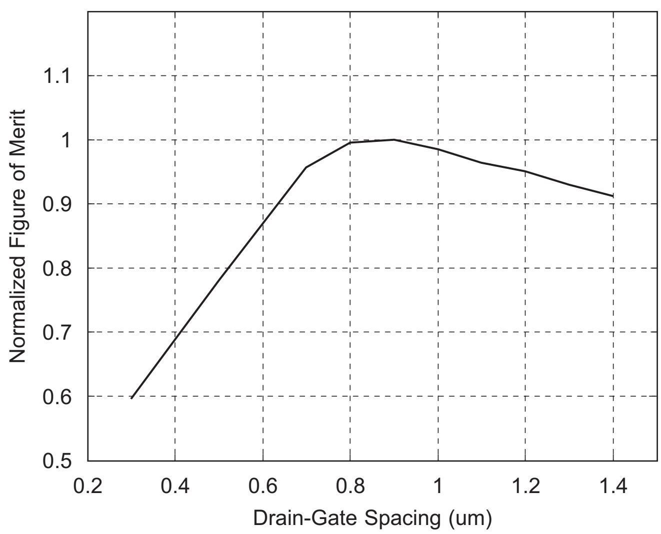

Fig. 8. Figure-of-merit as a function of drain–gate separation.

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that a guide to optimum design is available. In this particular case study, a drain–gate separation of around 0.9 μm gives the best results.

4. Conclusions

The effects of electrode spacing on the optical response of illuminated MESFETs have been presented. The FDTD simulations have been carried out using an energy-based model of carrier transport under illumination conditions. The optical performance of the device in response to a short-pulse illumination has been studied in terms of terminal photocurrent peak and response time as well as discharge time. Using a defined FoM, the simulation results showed that optimum electrode spacing can be achieved. The results also show that, unlike drain–gate spacing, source–gate spacing is not critical in this process.

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