OPTOELECTRONIC MODELING
OF HIGH SPEED MODULATED OPTICALLY-CONTROLED
GALLIUM ARSENIDE MICROWAVE SWITCHES

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ABSTRACT

In order to improve mixed optical-electrical microwave devices design, a novel modeling of opto-electronic phenomena as photoconduction effect has been achieved. Multiples photo-induced carriers generations/recombinations processes playing a part in semiconductor subtrates under laser illumination are taken into account and modeled by an equivalent electrical circuit. Various types of modulation applied on the optical signal, laser beam dimensions and intrinsic substrate material characteristics are integrated in order to define GaAs optically-controled switch application device properties. Optical effects on a RF signal propagation feeding microstrip circuit are reachable in both time and frequency domains through the Fourier transforms.

INTRODUCTION

In order to enhance data transmission flows, Telecom networks require ultrafast communications supports as, for example, optical fibers. In this case, integration of opto-electronic devices is necessary to secure transmission between optical links and data acquisition electronic systems. Hybrid simulations are usefull to perform such devices, which leads to the development of electrical models for optical phenomena representations.

In this paper, photoconduction effect is studied on LT-GaAs substrate, in order to achieve ultrafast microwave switch design excited by high speed modulated signal, and to validate optically-controled microwave circuits.

PHOTOCONDUCTION EFFECT ON MICROWAVE CIRCUITS

Semiconductor materials are sensitive to optical beam insulation at a wavelength λ satisfying the material absorption condition (1). Intrinsic conductivity is locally grown under laser illumination, leading to atoms/photons interferences. Electrons locally present in the semiconductor are brought to conduction band creating free charge carriers plasma layer which modifies material electrical properties. Photogenerated electron-hole pairs induce a local photoconductance G_g generation (2) depending on both semiconductor and light physical characteristics [1] like electrons and holes mobilities, the μ_n,μ_p, quantum efficiency η, the substrate absorption coefficient α, the air/substrate interface reflexion coefficient R, the incident optical power P_{opt} , the optical beam area A and the diameter W_{eff} , the gap length L_g , the ambipolar diffusion length L, the surface-carriers recombination speed v_s and the electrons lifetime ι.

$$\lambda_{opt}(\mu m) \leq \frac{1.24}{E_g(eV)} \tag{1}$$

$$G_g = \frac{e}{h\nu}(\mu_n+\mu_p)\eta\alpha\tau(1-R)\frac{P_{opt}}{A}\frac{w_{eff}}{L_g(1-\alpha^2L^2)}\left[\frac{1}{\alpha}-L\frac{\alpha L^2+v_s\tau}{L+v_s\tau}\right] \tag{2}$$

In this paper, photoconductive effect is applied to a photoswitching device (Fig.1), formed by a microstrip discontinuity line (gap) deposited on LT-GaAs substrate ($\varepsilon_r = 12.9$) and illuminated by picosecond optical pulses at λ equal to 860 nm.

Research works on GaAs [1], GaAs:Cr [2], Si [3] and InP [4] have been undertaken with several gap designs providing a 8 dB-maximum isolation between ON and OFF optical states and using a continuous optical source. Gap geometry, optical source and substrate material parameters have to be taken into account in order to optimize photoswitching structure and to enhance ON/OFF ratio [5,6]. High speed digital modulation introduced via optically controlled gaps on active MMIC has been demonstrated on GaAs substrate. Here, electrical modeling of opto-electronic phenomena is realized to perform a 30 dB @ 20 GHz isolation pulse-modulated optically controled LT-GaAs switch.

CARRIERS PLASMA LAYER PHOTOGENERATION

Photoconduction effect resumed various processes of carriers generation with direct and indirect recombinations taken place in impurities-filled semiconductors materials, under optical illumination. Assuming electro-neutrality equation and low injection mode, time-dependent electrons and holes densities expressions are governed by a two-coupled second order differential equations system (3,4) depending on substrate intrinsic parameters materials as the time-varying laser photons generation rate G, carriers capture coefficients $\beta_{n,p}$, the initial donor and acceptor atoms densities in the substrate $N_{D,A}$. System solutions enable time-dependent photoresistance $R_g(t)$ and associated photoconductance $G_g(t)$ expressions (5), assuming holes are negligible because of their low mobility compared to electrons and a time-dependent electrons density variation $\Delta n(t)$ with an initial value n_0 . $G_g(t)$ models the optoelectronic process via nonlinear time-varying electrons density $\Delta n(t)$ which depends itself on the photoconductive effect. $\Delta n(t)$ is driven by the optical G parameter which enables integration of modulated optical time-varying signals. Numerical calculations have been executed with a mathematical software in order to determine carriers densities variations versus time, from a constant, two states or exponential expression for G parameter, corresponding to continuous, digital or pulsed-mode optical modulation of carriers densities, induced by photoconductivity.

NON LINEAR PHOTORESISTANCE ELECTRICAL EQUIVALENT MODEL FOR MMIC DESIGN

Time-varying electrons and holes densities n(t) and p(t) expressions solved numerically are electrically modeled with a non-linear circuit. The parameters which define theoretical time-dependent equations are assimilated to a currents sum and lumped elements placed in parallel. Electrons and holes densities variations are symetrically designed by two identical circuits, loaded by a common element, through voltages expressions. Each electrical part includes a current source defining the optical signal characteristics G and a serial resistance-capacitance element which time constant is inversely proportionnal to $\beta_{n,p}$. Another capacitance is also added in order to obtain a scale unit factor between outpout calculated voltages n(t) and p(t) and physical densities data usually expressed in number of particles per volume. Electron density time variation is easily reachable in term of voltage and enables photoresistance time expression $R_g(t)$ as output parameter of the electrical model. Electrical simulations using different expressions for G parameter have been executed. For example, for a pulsed-mode optical input signal, the obtained electrons density growth (Fig.2) and photoresistance $R_g(t)$ (Fig.3) responses using this electrical developped model are identical to those resulting from mathematical resolution. The described model leads to efficient optimizations on switching performances between laser OFF and ON states. Isolation characteristic can be determine, knowing OFF state and ON state local resistance values. For example, with a pulsed-mode laser, the local resistance value of $40\text{k}\Omega$ in OFF state can be reduced to a 2Ω value at ON state during few picoseconds. Introducing this complete model in microwave softwares for MMIC devices design, optoelectronic simulations are achieved and are easily usable.

$$\frac{dn}{dt} = G - \beta_n n^2 - \beta_n N_A n + \beta_n np \tag{3}$$

$$\frac{dp}{dt} = G - \beta_p p^2 - \beta_p (N_D - N_A) p + \beta_p np \tag{4}$$

$$R_g(t) = \frac{d}{Aq \cdot \mu_n (n + \Delta n(t))} = \frac{1}{G_g(t)} \tag{5}$$

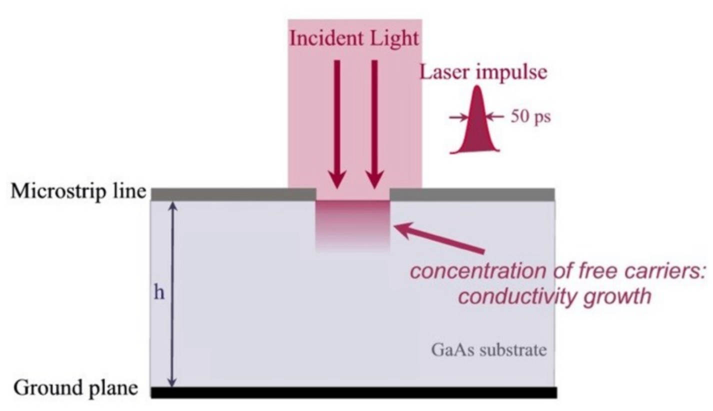

Fig.1: Photoconductive effect on a microstrip line discontinuity: Photoswitching device

ULTRAFAST LT-GaAs MICROWAVE PHOTOSWITCH PERFORMANCES: OPTICAL TO RF SIGNAL AMPLITUDE MODULATION

Photoswitching device consists of a 160 µm× 90 µm microstrip discontinuity line fed by a microwave signal at a f_o frequency. Pulse-modulated optical excitation inducing photoconductive effect modeled by the nonlinear electrical circuit is placed in parallel with the microstrip gap, generating a time-dependent photoresistance $R_g(t)$ usable for time-domain S-parameters simulations at f_o. Fast Fourier transforms from simulations are calculated in order to obtain frequency-domain S-parameters. Those last results are compared to frequency-domain S-parameters simulations values obtained from a reference circuit at f_o where ON and OFF states are synthetized by two constant resistance values corresponding to the photoresistance average values at ON and OFF states.

Photoswitching of the microwave signal by laser illumination is revealed through time-domain optoelectronic device response. Indeed, the microwave signal amplitude is actually modulated by the picosecond photoresistance pulsed shape with a Gaussian-type end-broadening response describing non-linear effects induced by semiconductor substrate characteristics. Thus, the electrical model for optoelectronic phenomena is more appropriate for optoelectronic structure simulation than usual microwave software in terms of carriers mobilities and recombination times integration in calculus. Various types of modulation on the optical signal have been introduced in the electrical model such as sinusoidal, digital or pulsed mode performing microwave signal switching and sampling at high frequency. For example, 50 ps FWHM optical laser pulses with 500 ps repetition period focused on a LT-GaAs substrate via the microstrip discontinuity can switch either a 20 GHz or a 50 GHz microwave signal (Fig.4,5) with a speed enhanced by the FWHM time order. ON/OFF ratios of 30.2 dB, 22.8 dB and 19.7 dB at a f_o frequency of 20, 40 and 60 GHZ respectively are performed with both optoelectronic and reference circuits simulations. Spectrum analyzer measurements have been done with a 2 GHz-modulating signal of 140 mW power continuous optical source ($\lambda = 860$ nm), exhibiting optical amplitude modulation of a 4 GHz microwave input signal (Fig.6).

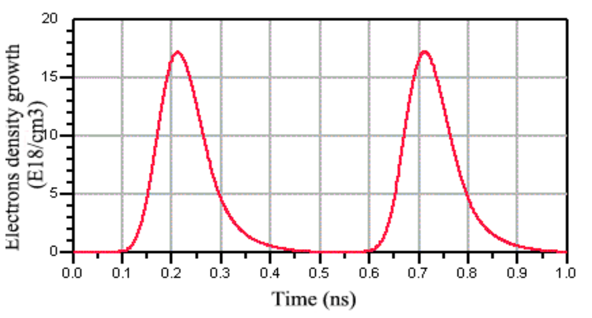

Fig.2: Time-varying electrons density representation from developped equivalent electrical circuit
(scale factor: 1 V ↔ 10^{18}atoms/cm^3)
Pulses repetition period $T_d = 500$ ps FWHM: $\tau = 50$ ps

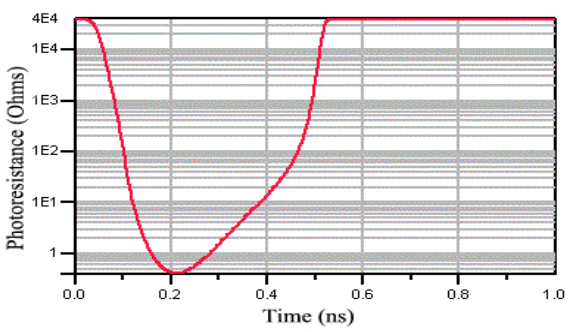

Fig.3: Single pulse induced time-varying photoresistance $R_g(t)$ simulated from equivalent electrical circuit in ohms (incident pulse centered at 200 ps)

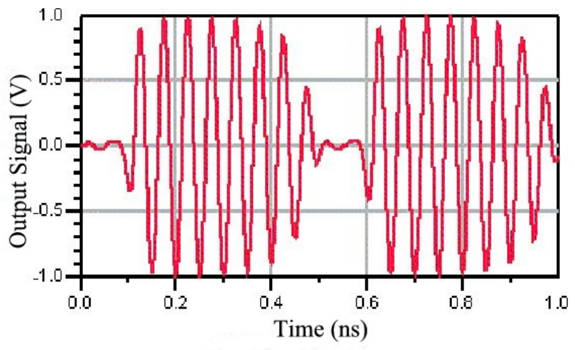

Fig.4: 20 GHz time-varying response signal
Optical induced-switching

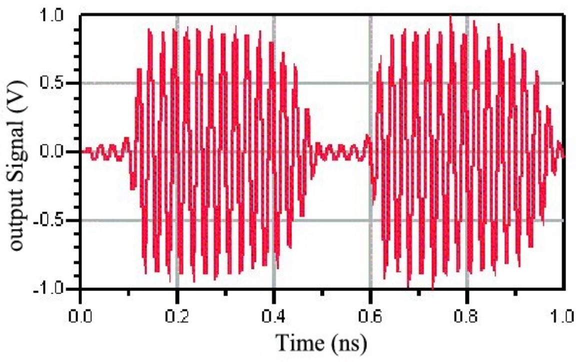

Fig.5: 50 GHz time-varying response signal

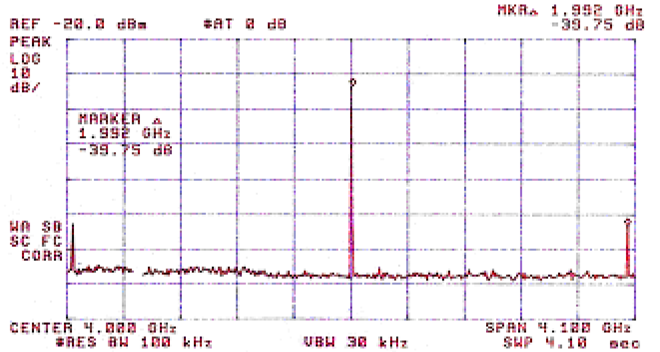

Fig.6: Amplitude modulation of microwave signal at 4 GHz by a 2 GHz signal on optical carrier

CONCLUSION

A novel modeling of photoconductive effect on a semiconductor substrate induced by modulated optical signal illumination has been validated with microwave simulations. The electrical model, optimized with continuous illumination and mathematical resolution, has the originality to describe optoelectronic process resulting from analogic and digital optical modulations. This model has been developped to anticipate the GaAs and LT-GaAs microwave microstrip switch behaviour: picosecond switching speed with pulsed-mode laser, and sampling of the microwave signal have been observed.

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