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On a Predictive Scheme of Slow Photoconductive Gain Evolution in Epitaxial Layer/Substrate Optoelectronic Nanodevices

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Abstract

The photoconductive response of the fundamental type of diodic nanodevice comprising a low resistivity, *n*-type epitaxial layer and a semi-insulating substrate is considered in terms of the optoelectronic parameter of photoconductive gain as experimentally measurable through monitoring the temporal evolution of conductivity current photoenhancement under continuous epilayer illumination-exposure. A modelling taking into account the built-in potential barrier of the interface of the epitaxial layer/substrate device (ESD) as well as its modification by the photovoltage induced within the illuminated ESD diode leads to predicting the technologically exploitable possibility of a notably slow photonic dose-evolution (exposure time-development) of the optonanoelectronics ESD photoconductive gain.

Keywords: Optoelectronic Nanodevices, Photoconductive Gain

1. Introduction

Characterisation of optoelectronic semiconductor micro/nano-devices is achievable through illumination-induced modification of fundamental transport properties. Thus, obtaining the dependence of different optoelectronic functionality parameters upon externally applied agents, such as incoming light wavelength and intensity, electric bias and ambient temperature, has been proving a powerful tool of investigations of ours [1-6], as well.

In the present paper, the photoconductive response of a type of diodic micro/nano-device comprising a low resistivity, n-type epitaxial layer and a semi-insulating substrate is considered in terms of the optoelectronic parameter of photoconductive gain as experimentally measurable through monitoring the temporal evolution of conductivity current photoenhancement under continuous epilayer exposure at room temperature. A modelling taking into account the built-in potential barrier of the interface of the epitaxial layer/substrate device (ESD) as well as its modification by the photovoltage induced within the illuminated ESD diode leads to predicting the technologically exploitable possibility of a notably slow photonic dose-evolution (exposure time-development) of the optonanoelectronics ESD photoconductive gain.

2. Modelling

Consider a semiconductor micro/nano-metric ESD under bias V, applied between the source (S) and the drain (D) of the active channel materialising within its epitaxial layer, through which an initial steady-state conductivity current I_0 flows. Let the device be illuminated from the active region side with photons of constant flux Φ (photons/(cm^2 s)) and of wavelength λ appropriate for their being capable of exciting interband transitions, incident normally to the conductivity current. Let, furthermore, the photoenhancement of the ESD conductivity current be I_{pe}. Then, the time rate of flow of photocarriers is (I_{pe}/e) (illumination-induced carriers/s), where e is the absolute electron charge, whereas the time rate of incidence of photons upon the device is (ΦA) (impinging photons/s), where A is the exposed area of the active region surface.

The ratio, now, of the rate (I_{pe}/e) of carrier photoresponse to the rate (ΦA) of incoming illumination photons constitutes the photoconductive gain (PG) Γ of the optoelectronic device, viz.

$$\Gamma = \left[\left(I_{pe} / e \right) / \left(\Phi A \right) \right]. \quad (1)$$

During the ESD illumination a charge Q_{pe} is injected owing to the photovoltaic effect, expressible as the product of the photovoltaic current I_{pv} and the photocarrier lifetime τ,

$$Q_{pe} = I_{pv} \tau . \quad (2)$$

On the other hand, the photoenhancement I_{pe} of the ESD conductivity current is given by this injected photocharge Q_{pe} divided by the transition time τ_{tr} needed by a carrier for traversing the distance between *S* and *D* of the active channel within the epitaxial layer, parallel to the applied external electric field:

$$I_{pe} = \left(Q_{pe} / \tau_{tr} \right). \quad (3)$$

This transition time τ_{tr} is calculable as the ratio of the ESD active channel length *l* over the carrier drift velocity v_d corresponding to the external electric field (*V*/*l*) applied within the conductivity channel through the experimental bias voltage *V* employed:

$$\tau_{tr} = l^2 / \left(\mu_d V \right), \quad (4)$$

with μ_d denoting an appropriate overall carrier mobility representing the drift velocity dependence upon biasing external electric field.

The crucially regulatory for the device's optoelectronic functionality ESD interface built-in electric field, now, is understood to be offering spatial separation of conjugate photogenerated carriers. This electron – hole segregation is leading to an evolving photomodification of the interfacial built-in potential energy barrier height (eV_{bi}) into an ever lowered one [$e(V_{bi} - V_{pv})$], owing to the each time effective forward biasing of the ESD interface by the induced photovoltage V_{pv} producing a continuing interfacial extension shrinkage in parallel to the interfacial barrier height lowering. Piling up on the opposite faces of the ESD interface, the either polarity photocarriers enjoy lifetime dilation [7] into τ from its value τ_0 valid in the absence of a recombination-suppressing quantum barrier:

$$\tau = \tau_0 \exp\left[e\left(V_{bi} - V_{pv} \right) / \left(kT \right) \right], \quad (5)$$

with *k* being Boltzmann constant and *T* being the ambient absolute temperature.

Furthermore, the photoresponse of the illuminated ESD (high – low) diode is describable by a current – voltage (photovoltaic) characteristic of the causality form [8]:

$$I_{pv} = I_{sr} \left\{ \exp\left[e\left(V_{pv} \right) / \left(\eta kT \right) \right] - 1 \right\}, \quad (6)$$

equivalent to

$$V_{pv} = \left(\eta kT / e \right) \ln\left[\left(I_{pv} / I_{sr} \right) + 1 \right], \quad (7)$$

with η being the ESD interface ideality factor (dependent upon prevailing charge

transfer mechanism) and I_{sr} being the saturation recombination current of the ESD diode, regulated [8] by the ESD interface built-in potential energy quantum barrier according to

$$I_{sr} = I_{sr}^{*} \exp\left[\left(-eV_{bi} \right) / \left(kT \right) \right], \quad (8)$$

where the pre-exponential factor I_{sr}^{*} is determined by the diffusion constant, the diffusion length, and the energy band effective density of states of the free carriers.

On the other hand, the photovoltaic current permeating the illuminated ESD interface (thus, directed normal to the epilayer active channel conductivity current) is conceivable as giving the temporal rate of collective carrier photogeneration, phenomenologically describable as the product between charge αe liberated per incoming photon and temporal rate Φ*A* of photon intaking, with the pertinent mean quantum efficiency α concerning each photon-induced, effected through interband transition, charge generation event:

$$I_{pv} = \alpha e \Phi A . \quad (9)$$

The ESD photoconductive gain Γ as given in Equation (1) can, therefore, be ultimately reexpressed, through Equations (2)-(5) and (7)-(9), as

$$\gamma = C + \ln \alpha + \ln \mu_d + \beta / T - \eta \ln\left[\left(I_{pv} / I_{sr} \right) + 1 \right], \quad (10)$$

or, equivalently,

$$\gamma = C + \ln \alpha + \ln \mu_d + \beta / T - \eta \ln\left[\Delta \alpha \Phi e^{\beta / T} + 1 \right], \quad (11)$$

where γ = lnΓ (logarithmic PG), C = $\ln(\tau_0 V/l)$, β = $(eV_{bi})/k$ (denoting an effective absolute temperature commensurate with the ESD interface built-in quantum barrier), and $\Delta = eA / I_{sr}^{*}$.

In these logarithmic PG γ causal expressions the intricate interplay of ambient absolute temperature *T*, illumination flux Φ, ESD interface ideality factor η, and carrier photogeneration quantum efficiency α is codified as interwoven with the ESD optoelectronic behaviour.

3. Predictive Scheme

Under experimental conditions of high ambient temperature *T* (e.g., room temperature) and relatively non-high impinging photon flux Φ, the ESD diode saturation-recombination current I_{sr} would be expected, alongside Equation (8), to be substantially greater than the respective photovoltaic current I_{pv} flowing through the ESD interface: $(I_{pv}/I_{sr}) \ll 1$. Such a proportion would render the fifth term on the RHS of Equations (10) and (11) approximately vanishing and the logarithmic PG γ cau-

sality simplifyingly expressible as

$$\gamma = C + \ln\alpha + \ln\mu_d + \beta/T\left[\text{for } \left(I_{pv}/I_{sr}\right) \square\ 1\right]. \quad (12)$$

During the ESD photoconductive response experiment, whilst the each time overall illumination-exposure time t_{expose} is increasing, the instantaneous cumulative photon dose $\delta = \Phi\ t_{\text{expose}}$ (photon flux times the each time total exposure time) intaken by the nanodevice is also being augmented. Thus, the measured ESD PG would be subsequently believed to exhibit a photonic dose-rate of evolution γ'_δ plausibly modeled by the partial differentiation of the above Equation (12) with respect to δ, with the first and fourth dose-independent RHS terms producing naught dose-rates of alteration:

$$\gamma'_\delta = \left(1/\alpha\right)\alpha'_\delta + \left(1/\mu_d\right)\left(\mu_d\right)'_\delta. \quad (13)$$

The essence of predictive scheme Equation (13), then, is that two major mechanisms would be expected to be influencing concurrently the character of ESD PG evolution against increasing cumulative intaken photon dose (increasing total exposure time): On the one hand, the dose-modification (at a rate of α'_δ) of the phenomenological mean quantum efficiency α concerning the collective carrier photogeneration and, on the other, the dose-variation (at a rate of $\left(\mu_d\right)'_\delta$) of the representative overall carrier mobility μ_d concerning the drift within the ESD conductivity channel under the biasing external electric field.

In particular, the photonic dose-modification of α would be expected to be of gradually increasing nature on the basis of evolving enhancement of interband transitions by an ever denser environment of intaken photons. Whereas, the photonic dose-variation of μ_d would be believed to be of (ultimately) decreasing nature owing to a consecutively strengthened mobility-limitting process pertaining to Brooks-Herring carrier scattering upon ever denser ionised (in the presence of ever more populous intaken photons) impurities within the ESD epilayer active region.

Such an interplay of concurrent mutually adverse mechanisms might, in the essence of Equation (13), allow for a notably slow dose-evolution (exposure time- development) of the optoelectronic ESD PG.

Indeed, a previous work of ours [9], concerning monitoring a constant-illumination quite slow photoconductivity-response room-temperature built-up in an InP:Fe ESD, appears supporting the present predictive scheme and encouraging its further experimental justification.

4. Conclusions

The photoconductive response of a type of diodic nanodevice comprising a low resistivity, n-type epitaxial layer and a semi-insulating substrate is considered in terms of the optoelectronic parameter of photoconductive gain as experimentally measurable through monitoring the temporal evolution of conductivity current photoenhancement under continuous epilayer exposure at room temperature. A modelling taking into account the built-in potential barrier of the interface of the epitaxial layer/substrate device (ESD) as well as its modification by the photovoltage induced within the illuminated ESD diode leads to predicting the technologically exploitable possibility of a notably slow photonic dose-evolution (exposure time-development) of the optonanoelectronics ESD photoconductive gain.

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