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InP:Fe NANODIODE CONDUCTIVITY CURRENT PERSISTENT PHOTOENHAMCEMENT DECAY

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Abstract: The temporal decay of the persistent photoenhancement of the conductivity current flowing through the active channel of two samples of a typical nanodevice comprising a low resistivity n-type InP:Fe epitaxial layer and a semi-insulating InP:Fe substrate is experimentally investigated at room temperature and interpreted via consideration of the functionality of the diodic interface potential barrier. A mean decay mechanism and its distinct regimes are singled out.

Keywords: photonic nanodevices, persistent photoconductivity

1. Introduction

The specific photonic parameter of conductivity current (CC) persistent photoenhancement (PPE) characterising InP diodic nanodevices having absorbed a regulated cumulative photonic dose of an wavelength capable of leading to photocarrier generation appears not to have been systematically monitored and discussed to-date. Its temporal decay, in particular, evolving after its saturation value has been obtained and then the illumination has been switched off, seems to remain in need of focused study. A previous investigation of ours [1] regarding the overall PPE response of two samples of InP:Fe nanodiodes has allowed for, among other series of measurements, experimental recording of the respective CC PPE decay, which we are herewith attempting to interpret in terms of the persistent photocarrier lifetime correlation with the diodic interface potential barrier functionality.

2. Modelling scheme

The epitaxial layer/substrate device (ESD) employed in this type of experiments functions under a 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.

In the first experimental stage the ESD is exposed either to successive regulated photon doses, provided at a constant photon flux Φ [photons/(cm^2 s)], or to continuous illumination at such a flux for an adequate uninterrupted period of time. The illumination photons impinge perpendicularly on the ESD epitaxial layer outer surface (to which the active channel conductivity current is parallel) and are of an wavelength λ appropriate for their exciting interband transitions creative of pairs of conjugate photocarriers. In the former case, monitoring of the gradual building-up of the pertinent conductivity photoenhancement (PPE) is achievable through recurrently measuring the PPE consequent upon each instantaneous cumulative photonic intake, between successive exposures and up till a saturation value is reached. In the latter, the PPE limitting saturation value is directly measurable after a continuous illumination exposure prescheduled to cover the saturation value cumulative photon dose deduced for the device according to the former procedure.

As regards, now, the photoenhancement $I_{\rm pe}$ of the (transverse with respect to the growth axis) ESD conductivity current (CC) induced during (continuous or of a regulated photon dose duration) exposure to illumination, it is given by the conductivity charge photoenhancement $Q_{\rm pe} = (I_{\rm pv}\tau)$ injected owing to the photovoltaic effect, thus expressible as the (parallel to the growth axis) photovoltaic current $I_{\rm pv}$ times the photocarrier lifetime τ, devided by the transition time $\tau_{\rm tr} = (L/v_d) = [L^2/(\mu_d V)]$ needed by a carrier for traversing the distance L between S and D of the active channel within the epitaxial layer parallel to the applied external biasing electric field (V/L) with a drift velocity v_d linked to this field through the overall drift mobility μ_d as $v_d = \mu_d(V/L)$:

$$I_{\rm pe} = \frac{Q_{\rm pe}}{\tau_{\rm tr}} = \frac{I_{\rm pv}\tau}{L^2/(\mu_d V)} = \frac{\alpha e \Phi A \tau}{L^2/(\mu_d V)} = \frac{\alpha e \Phi A}{L^2/(\mu_d V)}\ \tau_0 \exp\left(\frac{e(V_{\rm bi} - V_{\rm pv})}{kT}\right) \qquad (1)$$

where the photovoltaic current $I_{\rm pv}$ is written in terms of the inducing photon flux Φ as $I_{\rm pv} = \alpha e \Phi A$, with e being the (absolute value of the) elementary (electronic) charge, A being the exposed area of the active region surface and α being a mean quantum efficiency concerning each photon-induced , effected through interband transition, charge generation event, and where, also, the photocarrier lifetime τ is given in terms of the photovoltage $V_{\rm pv}$, modifying, as an effective forward bias, the ESD interface macroscopic potential barrier built-in voltage $V_{\rm bi}$, and the ambient absolute temperature T as [2]:

$$\tau = \tau_0 \exp\left(\frac{e(V_{\rm bi} - V_{\rm pv})}{kT}\right) \qquad (2)$$

with τ_0 being the photocarrier lifetime valid in the absence of the recombination-suppressing ESD interface macroscopic potential barrier and k being Boltzmann thermodynamic constant.

Furthermore, the photoresponse of the illuminated ESD diode is describable by a current-voltage (photovoltaic) characteristic of the form [3]:

$$I_{\mathrm{pv}} = I_{\mathrm{sr}} \left(\exp\left(\frac{eV_{\mathrm{pv}}}{\eta kT} \right) - 1 \right) \tag{3}$$

equivalent to

$$V_{\mathrm{pv}} = \frac{\eta kT}{e} \ln\left(\frac{I_{\mathrm{pv}}}{I_{\mathrm{sr}}} + 1 \right) \tag{4}$$

where η is an ESD diodic interface ideality factor and I_{sr} is the saturation recombination current of the ESD diode, regulated [4] by its interfacial built-in potential quantum barrier V_{bi} and by the ambient absolute temperature.

In the second experimental stage, following the establishment of the ESD PPE saturation state and performed with the illumination non-existent and the parasitic background light shielded away or effectively offset, the gradual decay of the PPE from the aforementioned limitting value of the first stage and down to less than its 30 % is registered through, usually, point measurements taken at regular minute intervals.

The decay index (DI) adopted in this study for monitoring the temporal relaxation of ESD active channel CC PPE is $\delta = \delta(t)$ defined as the actual instantaneous remaining CC PPE $I_{\mathrm{ppe}} = I_{\mathrm{ppe}}(t)$ reduced over illumination – regime saturation value and expressed percent:

$$\delta = \frac{I_{\mathrm{ppe}}}{I_{\mathrm{ppe,sat}}} 100\% \tag{5}$$

where the PPE saturation value $I_{\mathrm{ppe,sat}}$ would already causally be (somewhat) smaller, as indeed experimentally measures, than the ESD CC photoenhancement $I_{\mathrm{pe,f}}$ valid under illumination at the final step of the experimental first, PPE building-up, stage.

3. Experimental findings and interpretation

The laboratory findings concerning the CC PPE DI exhibited by the investigated two identical InP:Fe ESD samples are presented in Figure 1. Each sample, placed in a closed-He cryostat the window of which is sealed with a 25 μm thick Mylar sheet, comprises a 500 nm thick epitaxial layer of n-InP:Fe having a room temperature (RT) conductivity carrier concentration of $1.0 \cdot 10^{16}\,\mathrm{cm}^{-3}$ and a semi-insulating (SI) InP:Fe substrate having a RT carrier concentration of $2.68 \cdot 10^{8}\,\mathrm{cm}^{-3}$ (amounting to a specific resistivity of $1.1 \cdot 10^{7}\,\Omega$cm). The S and D orthogonal ohmic contacts, separated by an active channel length L of 5.0 μm parallel to the epitaxial layer surface, are of the Au:Ge type. The illumination system consists of a small 250 W halogen lamp having an external elliptical mirror and a computer-controlled Oriel Optics monochromator. In the PPE building-up stage,

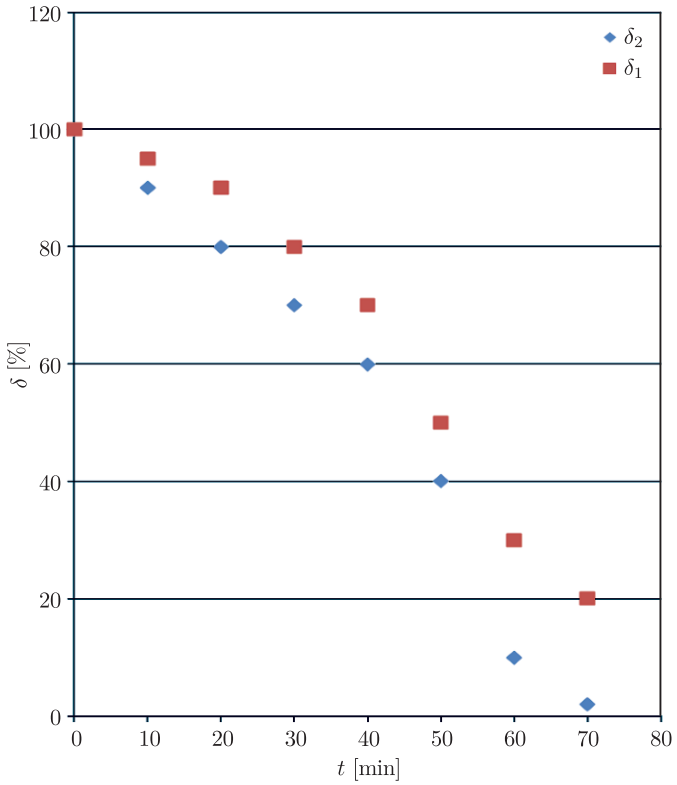

Figure 1. Conductivity current persistent photoenhancement (reduced to percentage with respect to saturation value obtained at the end of its growth period, prior to removing the illumination) δ versus decaying time t (in min) for two representative samples of InP:Fe n-type epitaxial layer/substrate device: δ_1 (represented by squares) concerns the effect of prior illumination of wavelength $\lambda = 925.4\,\mathrm{nm}$, commensurate with the regular energy gap of the InP semiconductor, whereas δ_2 (represented by diamonds) concerns the effect of prior illuminationthat of $\lambda = 850\,\mathrm{nm}$

Sample 1 is illuminated with photons of wavelength $\lambda_1 = 925.4\,\mathrm{nm}$, commensurate with the regular energy gap of the InP semiconductor, whereas Sample 2 with over-interband photons of wavelength $\lambda_2 = 850\,\mathrm{nm}$. The RT ESD active layer CC is measured by a Keithley electrometer.

A qualitative interpretation of the CC PPE decay dynamics appearing in Figure 1 derives from realising that after illumination removal the conjugate photocarriers spatially separated by the ESD interface saturated photovoltage – modified built-in potential barrier $(V_{\mathrm{bi}} - V_{\mathrm{pv,s}})$ are gradually recombining at a mean temporal rate ν given by the inverse of their ESD interface barrier – enhanced lifetime τ of Equation (2) without, now, the illumination-induced regeneration mechanism being operative. This mean photocarrier recombination rate $\nu = (1/\tau)$ is expectedly high for RT, as verified by the rather steep slope of the experimental trend $\delta(t)$ denoted in Figure 1. It is, also, noteworthy that both samples, regardless of the (over-)interband wavelength of the satu-

rated PPE preparation, exhibit the same two functional kinds of major decay regimes, in terms of regime slope and regime duration, as adequately witnessed in Figure 1.

4. Conclusion

The temporal decay of the persistent photoenhancement of the conductivity current flowing through the active channel of two samples of a typical nanodevice comprising a low resistivity n-type InP:Fe epitaxial layer and a semi-insulating InP:Fe substrate is experimentally investigated at room temperature and interpreted on the basis of mean photocarrier post-illumination recombination rate. Two functional kinds of major decay regimes, in terms of regime slope and regime duration, are singled out.

We are, therefore, intending to continue deciphering the exact decay mechanisms of ESD CC PPE through further study of similar sample experimental findings, in the belief that PPE decay dynamics is also crucial for predicting the safe effective temporal interval for further technological exploitations of solar photovoltaic sustainable-energy systems.

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