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Determination of persistent photoconductivity within semiconductor epitaxial layers by photoconductive gain

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A model is proposed for the determination of the saturation value of persistent photoconductivity (PP) within illuminated semiconductor epitaxial layers, based upon the monitoring of the optoelectronic parameter of photoconductive gain of the respective epitaxial layer-substrate devices (ESD). The model takes into account the functionality of the macroscopic potential-energy barrier existing within the ESD interface, as well as the control of ionized-impurity scattering over the carrier mobility at low temperatures, where PP is observable.

I. INTRODUCTION

Optimization of semiconductor device performance is promoted by invoking illumination-enhanced charge-transfer mechanisms through potential barriers and studying the dependence of the device's optoelectronic response upon externally applied agents, such as light wavelength and intensity, electric bias, and temperature.[1-5]

In the present work, a model is proposed for determining the saturated persistent photoconductivity (PP) within an illuminated semiconductor epitaxial layer at a given temperature on the basis of the monitored photoconductive gain (PG) of the respective epitaxial layer-substrate device (ESD).

The saturated PP value is expressed in terms of the associated excess sheet electron density $[\Delta(nd)]_{\text{sat}}$ and the joint effect of the selected stimulating photon flux F and the resulting measured photoconductive gain G is represented by their product G^*, termed effective photoconductive gain.

The model makes use of the function of the macroscopic potential barrier[6,7] existing between the epilayer and the substrate of the ESD configuration along with the temperature dependence of the ionized-impurity-limited carrier mobility given by the Brooks-Herring theory.[8]

The predictions of the model coincide satisfactorily with experimental results obtained from GaAs epitaxial layers produced by Si ion implantation into undoped semi-insulating GaAs substrates.

II. THE MODEL

A. Persistent photoconductivity

In the case of illumination of an ESD device at sufficiently low temperatures, the photoeffects persist after switching off the light, giving rise to PP. As is well known, two major interpretations of the PP effect have been adopted to date.

The first interpretation employs the behavior of the macroscopic potential barrier due to band bending at the ESD interface. The functionality of such a potential relief was suggested by Rose,[9] then described by Vul, Nabiev, Petrosyan, and Shik,[10] and systematically studied by Queisser and Theodorou.[11,12]

The second interpretation assumes a microscopic energy barrier that suppresses the recombination of the photogenerated electron-hole pairs. Such a barrier, first proposed by Wright, Downey, and Canning[13] to account for the PP effect in CdS, is thought to arise from impurity atoms or donor-vacancy complexes (usually called *DX* centers).

In the present discussion, we shall be following the first of the above attributions of the PP effect, which has previously[14] enabled us to perform a consistent characterization of ESD interfaces.

B. Photoconductive gain

The internal amplification mechanism applicable to the optimal performance of an ESD device is describable by the optoelectronic parameter of the PG.

The photoconductive gain G of an illuminated ESD under bias V is defined as the ratio of the number of photogenerated carriers contributing to the conductivity current flow in the unit of time to the number of photons impinging upon the device active-region (epitaxial-layer) surface in the unit of time:

$$G=[(\Delta I/e)/(FA)] , \tag{1}$$

where ΔI is the increment of the conductivity current due to illumination, e is the electronic charge, F is the incident photon flux, and A is the exposed active-region surface area.

The illumination enhancement ΔI of the conductivity current equals the injected charge ΔQ, driven by the photovoltaic current through the ESD interface towards the device active channel, divided by the transition time t_{tr} needed by a carrier to traverse the distance L between the source (S) and the drain (D) of the active channel within the epitaxial layer, parallel to the applied external electric field (V/L)

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$$\Delta I = \Delta Q / t_{\text{tr}} \ , \tag{2}$$

where the transition time t_{tr} is the S-D distance L over the carrier drift velocity $[\mu_d(V/L)]$, μ_d being the carrier drift mobility against the external electric field (V/L) activated between S and D

$$t_{\text{tr}} = L/[\mu_d(V/L)] \ . \tag{3}$$

Therefore, the PG definition Eq. (1) reads, due to relations (2) and (3),

$$G = (1/F)(V/L^2)\mu_d[\Delta Q/(eA)] \ . \tag{4}$$

C. Derivation of PP from PG

In a previous paper[15] we predicted a functional dependence of photoconductive gain G upon absolute temperature T and incident photon flux F, valid for the low-temperature regime, of the form

$$\ln G = \text{const} + (1-n)eV_{\text{bi}}/(kT) - n \ln F \ , \tag{5}$$

where n is the ESD interface ideality factor and eV_{bi} is the ESD interface built-in macroscopic potential barrier.

We then remarked that in this low-temperature domain the ESD interface ideality factor n approaches unity, in view of the fact that the diffusion charge-transfer mechanism becomes dominant. Therefore, PG ceases to depend upon temperature:

$$\ln G = \text{const} - \ln F \ , \tag{6}$$

or, equivalently,

$$FG = \text{const} \ . \tag{7}$$

The prediction of relation (6) was afterwards met by experimental investigations,[16] concerning the low-temperature regime below 100 K, where the PP effect is also observable.

In view of (7), we feel that the product (FG), representing the joint effect of the incoming flux F, as the stimulant, and the measured photoconductive gain G, as the response, could be handled as an integral entity, which we term the effective photoconductive gain G^*. G^* has the important property of being constant for all those low absolute temperatures for which the PP effect is pronounced,[17] that is , for which the separated photocarrier lifetime is significantly enhanced by the presence of the ESD interface macroscopic potential barrier.[18] Equation (4), rewritten in terms of G^*, yields

$$G^* = (V/L^2)\mu_d[\Delta Q/(eA)] \ . \tag{8}$$

We now proceed to directly relate the saturated PP value $[\Delta(nd)]_{\text{sat}}$ to the effective photoconductive gain G^*. This is based on the following assumptions.

(a) Under continuous exposure to light, the charge ΔQ, injected into the ESD active channel by the photovoltaic current flowing through the device interface, has well reached the saturation value that it would sequentially approach if it were gradually accumulating by successive exposures of the ESD to total photon dose increments in a PP experiment.

(b) In the steady state, established under constant illumination, the recombination of the accumulated charge ΔQ is suppressed by the ESD interface potential barrier prolonging the lifetime of the spatially separated conjugate photocarriers, in the same way that the active channel photoelectrons are persisting in the PP experiment.

We therefore conclude that the saturation value $[\Delta(nd)]_{\text{sat}}$ of the sheet photocarrier density that is going to be persisting after switching off the illumination in the PP experiment is equal to the steady-state areal concentration $[\Delta Q/(eA)]$ of the photocarriers $(\Delta Q/e)$ injected under continuous exposure to light into the ESD active channel in the PG experiment:

$$[\Delta(nd)]_{\text{sat}} = [\Delta Q/(eA)] \ . \tag{9}$$

Therefore, (8) transforms, due to (9), into

$$[\Delta(nd)]_{\text{sat}} = (L^2/V)(1/\mu_d)G^* \ . \tag{10}$$

It is noteworthy that the model Eq. (10) allows for the experimentally observed monotonic decrease of $[\Delta(nd)]_{\text{sat}}$ with temperature T, consequent upon the shortening of the separated persisting photocarrier lifetime.[19]

Indeed, while the effective photoconductive gain G^* remains constant throughout the low-temperature regime, according to (7), the carrier mobility μ_d increases monotonically with T, as determined by the scattering upon ionized impurities, described by the Brooks-Herring considerations.[20,21]

III. APPLICATION

A Experimental details

The samples used in the PG and PP experiments have been obtained by Si ion implantation into undoped semi-insulating GaAs substrates, using ion-beam energies of the order of 100 keV resulting in epitaxial layer depths of the order of 0.2 μm, whereas the thicknesses of the substrates are of the order of 300 μm. The Si donor density within the ion-implanted epitaxial layers is of the order of 5×10^{16} cm^{-3}, whereas the carrier concentration within the substrates is of the order of 1×10^{7} cm^{-3}. The length of the active channel within the epilayers is of the order of 10 μm.

The PG measurements are performed under low external electric bias of the order of 40 mV, applied between the source S and the drain D of the epitaxial layer surface. The light source is an array of red LED's (660 nm) connected to a high-stability current source. The photon flux, varying within four orders of magnitude between 10^{10} photons/(cm^2 s) and 10^{14} photons/(cm^2 s), is measured with a calibrated Si p-n photodiode.

The PP measurements are performed with a single red LED as the light source and with a constant photon flux of 10^{10} photons/(cm^{2}s). The cumulative photon dose ranges from 10^{10} to 10^{13} photons/cm^2 and is obtained by progressively increasing the total exposure time. The critical-dose value for saturation of the PP measurements does not exceed 5×10^{12} photons/cm^2.

Each sample is characterized by means of the van der Pauw method,[22] held in a closed-cycle He cryostat, in the

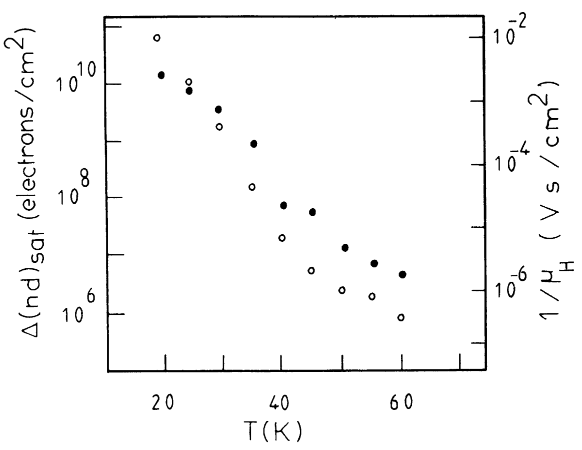

FIG. 1. The saturation value $[\Delta(nd)]_{sat}$ of the persisting sheet majority carrier (electron) density within a representative illuminated n-type GaAs epitaxial layer, as determined through the effective photoconductive gain G^* measurements according to the model equation (10), as a function of absolute temperature T (light circles). Also, the inverse $1/\mu_H$ of the measured Hall mobility μ_H vs T (dark circles). The $[\Delta(nd)]_{sat}=f(T)$ experimental curve follows the monotonic decrease inherent in the proposed model and agrees with the independent findings of the PP experiment throughout the low-temperature regime [20 K, 60 K]. The temperature spectrum of $1/\mu_H$ presents some similarity to the $[\Delta(nd)]_{sat}=f(T)$ curve.

low-temperature region between 20 and 60 K. The carrier mobility is estimated by the ratio of the saturation values of sheet-electron conductivity and sheet-electron density.

B. Experimental curves

The saturation value $[\Delta(nd)]_{sat}$ of the persisting sheet electron density within a representative GaAs epitaxial layer, as determined through the effective photoconductive gain G^* measurements according to the model equation (10), versus absolute temperature T is shown in Fig. 1 (light circles), in which the inverse $1/\mu_H$ of the measured Hall mobility μ_H vs T is also plotted (dark circles). The $[\Delta(nd)]_{sat}=f(T)$ experimental curve exhibits the monotonic decrease inherent in the proposed model.

It also coincides within experimental error with the independent findings of the PP experiment for the entire low-temperature regime [20 K, 60 K].

On the other hand, the $1/\mu_H=g(T)$ experimental curve does present some similarity with the $[\Delta(nd)]_{sat}=f(T)$ plot. This could argue in favor of the plausibility of the model equation (10).

IV. CONCLUSION

In the present paper a model is proposed for the determination of the saturation value $[\Delta(nd)]_{sat}$ of the PP parameter of excess sheet majority carrier density within illuminated semiconductor epitaxial layers, utilizing the monitoring of the respective ESD optoelectronic response in terms of the measurement of the effective photoconductive gain G^*. The model employs the functionality of the ESD interface macroscopic potential barrier as well as the Brooks-Herring theory for the low-temperature mobility of the probed epilayers. The model is applied to the experimental findings obtained from ion-implanted n-type GaAs epitaxial layers.

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