Persistent photoconductivity and *DX* centers

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Persistent photoconductivity is commonly attributed to the existence of *DX* centers within the semiconductor layer under investigation. Based on this assumption, we develop a model that clearly predicts a linear-increase regime for the dependence of the sheet density of the persisting carriers upon cumulative photon dose, before saturation. The discrepancy between this expected linearity and the experimental findings of several authors, as well as those deriving from the wide variety of our samples, renders implausible the speculation that *DX* centers are an inevitable prerequisite for the observation of the persistent-photoconductivity effect and renews consideration of the possible validity of an alternative model of macroscopic potential barriers inducing the persistent photoconductivity.

As is well known, two major interpretations of the persistent photoconductivity (PP) effect have been adopted to date.

The first interpretation is based on the assumption of a macroscopic potential barrier due to band bending at the surfaces, interfaces, or around doping inhomogeneities in semiconductor devices. The functionality of such a potential relief was early suggested by Rose,[1] then described by Vul *et al.*,[2] and systematically studied by Queisser and Theodorou.[3,4]

The second interpretation assumes a microscopic energy barrier that suppresses the recombination of the photogenerated electron-hole pairs.

The carriers in this case are excited from impurity centers with photon energies smaller than the band gap. Such a barrier, first proposed by Wright, Downey, and Canning[5] to account for the PP effect in CdS, is thought to arise from impurity atoms or donor-vacancy complexes (usually called *DX* centers). A configuration coordinate model, utilized by Lang, Logan, and Jaros[6] in an $Al_xGa_{1-x}As/GaAs$ structure, describes a situation where the empty defect level lies above the conduction-band minimum while the occupied level lies within the band gap.

In the present discussion we shall mainly be following the initial approach of Wright, Downey, and Canning referring to the generic structure of Fig. 1. This represents an epitaxial layer of total depth d containing one type of *DX* center of uniform volume density N_0 and exposed to a uniform photon flux ϕ_0 striking its upper surface. At a certain depth x below the illuminated surface the local value of the photon flux is ϕ and the local value of the ionized *DX* center concentration at cumulative exposure time t is N. The cross section for the capture of photons by the *DX* centers is σ.

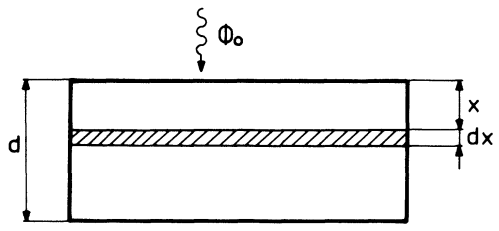

FIG. 1. Generic structure for the observation of the PP effect. The epitaxial layer of total depth d is exposed to a uniform photon flux ϕ_0.

Allowing for only one persisting electron to be activated from each *DX* center, the depth rate of decrease $(d\phi/dx)$ of the local photon flux ϕ and the time rate of increase (dN/dt) of the local instantaneous concentration N of the photoionized *DX* centers are given, respectively, by the following equations:

$$d\phi/dx=-\phi\sigma(N_0-N) \tag{1}$$

and

$$dN/dt=\phi\sigma(N_0-N)\ . \tag{2}$$

Solving the system of the above equations for the local instantaneous ionized *DX*-center density N as a function of total exposure time t, we obtain

$$N=N_0\{1-\exp(\sigma N_0 x)\times[\exp(\sigma N_0 x)+\exp(\sigma\phi_0 t)-1]^{-1}\}\ . \tag{3}$$

Given that the instantaneous cumulative photon dose Q entering the sample is

$$Q=\phi_0 t\ , \tag{4}$$

the sheet density $\Delta(nd)$ of the persisting electrons within the illuminated sample, formally obtained by

$$\Delta(nd)=\int_0^d(N\,dx) \tag{5}$$

is determined, according to formula (3), as

$$\Delta(nd)=N_0 d+(1/\sigma)\ln\{\exp(\sigma Q)[\exp(\sigma Q)+\exp(\sigma N_0 d)-1]^{-1}\}\ . \tag{6}$$

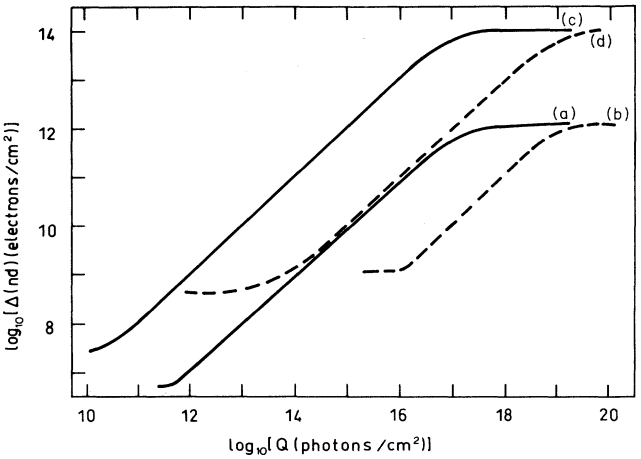

FIG. 2. Dependence of sheet persisting electron density $\Delta(nd)$ upon cumulative photon dose Q, according to the exact theoretical equation (6), for four cases with $N_0=1.0\times10^{18}$ cm^{-3}. Curve a: $d=10$ nm, $\sigma=1.0\times10^{-17}$ cm^2; curve b: $d=10$ nm, $\sigma=1.0\times10^{-19}$ cm^2; curve c: $d=1000$ nm, $\sigma=1.0\times10^{-17}$ cm^2; curve d: $d=1000$ nm, $\sigma=1.0\times10^{-19}$ cm^2.

For that interval of values of the cumulative photon dose Q for which $\sigma Q \ll 1$ and under the additional assumption for the sample parameters that $\sigma N_0 d \ll 1$, the above exact dose dependence (6) of the sheet concentration $\Delta(nd)$ of the persisting electrons is easily simplified to the expression

$$\Delta(nd)=N_0 d\sigma Q \tag{7}$$

or, equivalently, to the expression

$$\log_{10}[\Delta(nd)]=\log_{10}(N_0 d\sigma)+\log_{10}Q\ . \tag{8}$$

That is, the conditions $\sigma Q \ll 1$ and $\sigma N_0 d \ll 1$ label a linear-increase regime in the Q dependence of $\Delta(nd)$, provided that the occurrence of PP results from the microscopic potential barrier.

Figure 2 shows the exact Q dependence of $\Delta(nd)$, as described by Eq. (6), for four cases of the generic structure of Fig. 1. For curves a and b the epitaxial layer depth d is taken to be equal to 10 nm and the uniform DX-center concentration N_0 is equal to 1.0×10^{18} cm^{-3}. The photon-capture cross section equals 1.0×10^{-17} cm^2 for the first epilayer (curve a) and 1.0×10^{-19} cm^2 for the second (curve b). The epilayer parameters for curves c and d are the same as for curves a and b, respectively, with the only difference being that the structure depth d is now taken equal to 1000 nm.

The following features of Fig. 2 are worth noticing.

(i) Each $\log_{10}[\Delta(nd)]=f(\log_{10}Q)$ curve incorporates a linear-increase regime of slope equal to 1 and range R on the $\log_{10}Q$ axis dependent upon the values of the σ and d epilayer parameters, in accordance with expression (8) and the conditions under which it holds.

(ii) The $\log_{10}Q$ range R of this linearity increases with the epilayer depth d, for constant values of the σ and N_0 parameters.

(iii) The $\log_{10}Q$ range R of the linearity increases with the photon-capture cross section σ of the existing DX centers within the epilayer, for constant values of the d and N_0 parameters.

(iv) Each $\log_{10}[\Delta(nd)]=f(\log_{10}Q)$ curve reaches saturation once the sheet density $\Delta(nd)$ of the persisting electrons becomes equal to the total sheet density $(N_0 d)$ of the DX centers within the epilayer.

The aforementioned are the predictions of an interpretation of the PP effect based upon the assumption of the large lattice relaxation of the supposedly functional DX centers. Nevertheless, there is no sound experimental evidence of the buildup of PP in the literature substantiating such a model. This holds prominently true for GaAs and $Al_xGa_{1-x}As$ systems, for which, however, there is a strong tendency by several authors to cite the notion of DX centers as a synonym for the PP effect.

In this context, it seems worth recalling that an analogous attempt to devise a simple model, which would ac-

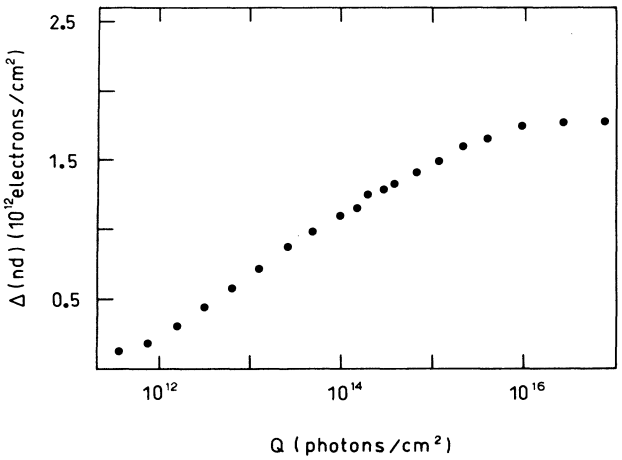

FIG. 3. Dependence of sheet electron density $\Delta(nd)$ upon photon dose Q, according to Ref. 3, for an N-type GaAs epitaxial layer with $d=300$ nm, at 32 K.

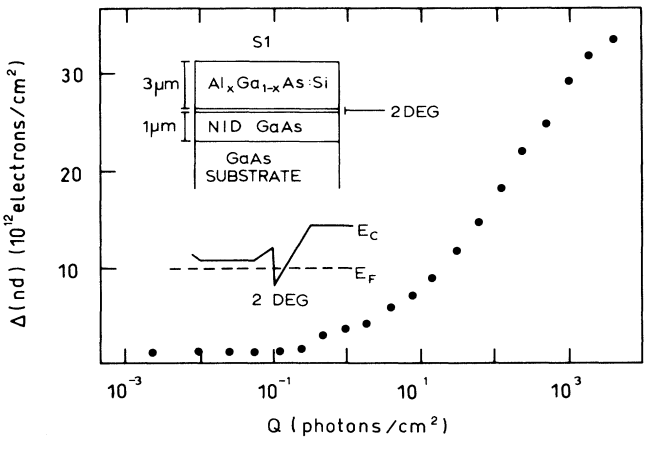

FIG. 4. Sheet persisting electron density $\Delta(nd)$ vs cumulative photon dose Q (reduced with respect to a reference value) for layered sample $S1$.

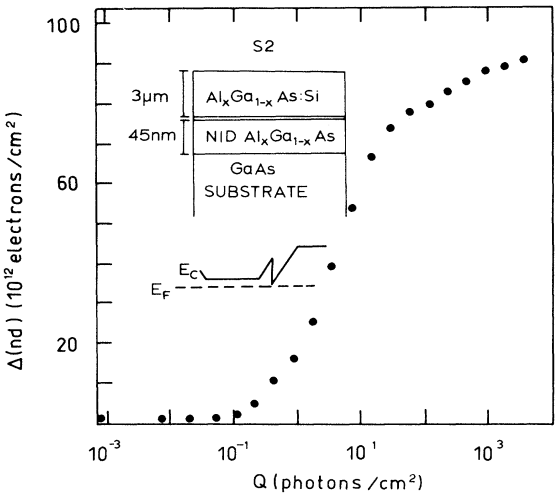

FIG. 5. Dependence of sheet electron density $\Delta(nd)$ upon photon dose Q for sample $S2$.

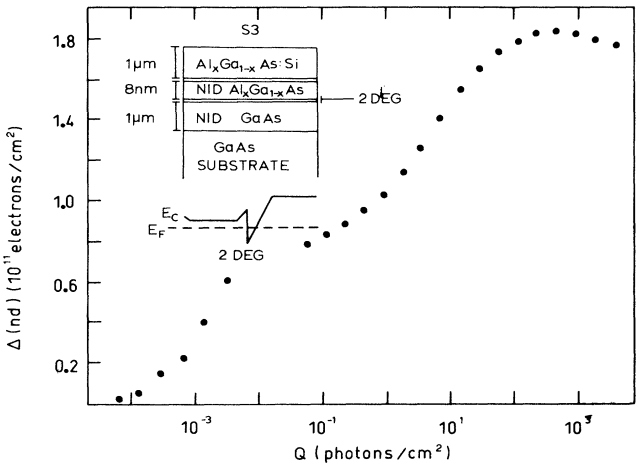

FIG. 6. Sheet electron concentration $\Delta(nd)$ as a function of photon dose Q for sample $S3$.

count satisfactorily for the experimentally observed behavior of $\Delta(nd)$ vs Q in N-type GaAs epitaxial layers, undertaken by Queisser and Theodorou[3] in their early PP paper proved successful: It predicted an extensive approximately logarithmic regime in the Q dependence of $\Delta(nd)$, which was rigorously verified by experiment. The model assumed that the result of the macroscopic potential barrier between the N-type, low resistivity epitaxial layer and the semi-insulating substrate was the spatial separation of the photogenerated partner carriers and the subsequent prolonging of the separated photocarrier lifetime.[7,8] From this paper we produce Fig. 3. In addition, the same authors[9] have plausibly simulated the temporal decay of PP in epitaxial GaAs and interfaces of $Al_xGa_{1-x}As$ heterostructures, on which they have experimented, by means of the properties of the device interface barrier.

Moreover, in order to furnish further and stronger indications that the DX-center model for PP investigated in the present paper lacks verification by research, we measured different epitaxial samples and monitored the detailed dependence of $\Delta(nd)$ upon Q.

The sheet persisting electron concentration versus cumulative photon dose for three representative samples (samples $S1$, $S2$, and $S3$) appears in Figs. 4–6. It is clearly evident for all samples that $\Delta(nd)$ increases slowly as Q scans many orders of magnitude, thus not allowing for the linear-increase regime in the Q dependence of $\Delta(nd)$, which we have proved to be the main identifying feature of a possibly underlying DX-center-like mechanism for the materialization of PP. Another interesting suggestion of these experimental curves is that the peculiarities of the functional dependence are critically sensitive to the exact type of the layered structure under study.

In conclusion, in this work we have argued that it is misleading to automatically attribute the PP observation to the inevitable existence of DX centers in semiconductor layered structures. Instead, one should primarily measure the buildup and decay kinetics of the phenomenon, and only then attempt to develop any model that would fit the research findings acceptably. Naturally, we could not exclude the mere existence of deep donors in GaAs-based samples, where they partially contribute to the persisting electron number but not necessarily to the persistent nature of the electrons.

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