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Hall-Effect Analysis of Persistent Photocurrents in *n*-GaAs Layers

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The buildup of persistent photoconductivity, presently a controversial phenomenon, is observed by measuring densities and mobilities of photoinduced excess electrons in thin *n*-GaAs layers between successive illuminations. Evidence from this novel type of analysis supports a model assuming charge separation by macroscopic potential barriers. We explain quantitatively how the photon dose logarithmically increases the number, but not necessarily the density, of persisting carriers and ascribe mobility enhancements to screening of ionized impurities.

Many semiconductors exhibit persistent photocurrents (PP): A photoinduced conductivity increment persists *after* the illumination, often with immeasurably long time constants.[1-7] Two conflicting interpretations presently exist. The first assumes *macroscopic* potential barriers, such as junctions or surface barriers, which separate spatially the photogenerated electron/hole pairs to suppress their recombination.[1-4] The second interpretation postulates *microscopic* barriers against recombination due to impurity atoms with large lattice relaxations.[5-7]

Interest in this unusual phenomenon has been recently rekindled. Studies of two-dimensional electron gases at semiconductor interfaces rely on PP to enhance electron densities.[8] Interpretations of atomistic properties of deep impurities in semiconductors have been based on PP observations.[6,7] Enhancement of carrier mobility by spatial separation of liberated carriers from their dopant ions ("modulation doping")[9] may be related to PP. Quantitative information is needed to describe lateral charge transport in very thin semiconductor layers near surfaces. This would be of interest for quantum effects from reduced dimensionality[10] as well as for applications, such as charge-coupled devices[11] or memories.[2]

This paper describes PP in well-defined layers of GaAs at low photon excitation levels. We are able to observe and explain for the first time the transient buildup of PP by using the Hall effect with high resolution to measure both density n and mobility μ of the excess electrons in thin n-type layers on high-resistivity substrates. This technique, which yields more information than simple conductance measurements, is shown here to furnish quantitative details about geometric structure and electronic transport. The method thus promises to become a novel technique for analysis of semiconductors interfaces. We obtain clear evidence for the model, assuming macroscopic barriers.

Our specimens have thin (width $d = 0.3-10\ \mu m$) epitaxial layers of various donor content, grown by liquid-phase epitaxy on Cr-doped semi-insulating GaAs substrates. The Hall effect is measured on cloverleaf-shaped samples with Sn contacts, using the van der Pauw technique.[12] An automated apparatus is used with great attention to temperature control; the magnetic field is 0.5 T.[13] Illumination of the sample is achieved through a glass fiber, using various light sources (lasers, lamps with or without spectrometer).[13]

Our measurements are concentrated in the temperature regime of ionized impurity scattering (from about 10 to 70 K). Figure 1 shows typical results, here for light of 815 nm, which just suffices to excite pairs across the band gap. A flux φ_0 of 10^{13} photons/cm^2 s is used. PP was observed in many samples, but restricted to layer thicknesses below 5 μm, indicating that the effect is related to the presence of the layer/substrate interface, which must be within a few diffusion lengths of the pair-generation site. We can therefore exclude bulk and surface mechanisms causing PP and conclude that it is the macroscopic layer/substrate potential barrier that separates a fraction of the generated carriers pairs, leads

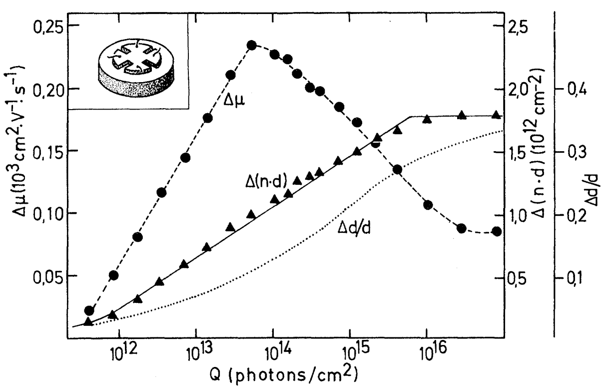

FIG. 1. Persistent excess electron area density $\Delta(nd)$ (triangles) and excess Hall mobility $\Delta\mu$ (circles) measured in the dark after cumulative photon dose Q, for an n-type GaAs layer of thickness $d_0 = 0.3\ \mu m$, at 32 K. The mobility μ_0 in the dark prior to the first illumination was 2600 cm^2/V s and $(nd)_0$ was 5×10^{12} cm^{-2} (errors in measurements of μ and nd smaller than 0.1%). Photon dose was administered by increasing exposure time, with a flux of 10^{13} photons/cm^2 s (error is ±30%). The full $\Delta(nd) = f(Q)$ curve represents theory of Eq. (3) (see text). The dotted $\Delta d/d = f(Q)$ curve (variation of layer width) was calculated using the $\Delta\mu = f(Q)$ dashed curve (see text). Inset: sample with layer on substrate. Current flows laterally, magnetic field and illumination perpendicular to the surface. Typical diameter of layer about 5 mm.

to a storage of the holes within the substrate, and thus precludes recombination after the illumination.

We observe PP irrespective of photon energy, from 2 eV to about 1 eV, which indicates that absorption by impurities (in the substrate) can also generate carriers which persist. The total photon dose at a given wavelength is decisive; identical results are obtained by reducing illumination intensity and simultaneously increasing exposure time by identical factors. The decay of PP is immeasurably slow below 80 K; heating above 200 K, however, restores the original status (to better than 0.1%) found prior to illumination.

Consider first the buildup of excess electron density Δn by a cumulative photon dose Q. The Hall coefficient does not yield the density n directly, but only the product of density times layer width (nd). This fact is important since the width d of the conducting layer may increase due to a reduction of the width w of the adjacent space-charge region. Plotted in Fig. 1 is $\Delta(nd)$, which is the value of (nd) after illumination minus the original "dark value" of $(nd)_0 = 5\times10^{12}$ electrons/cm^2. The photon dose increases $\Delta(nd)$ because holes are separated from their partner electrons by the built-in electric field of the substrate/layer interface.

The buildup of $\Delta(nd)$ is surprisingly slow; several orders of magnitude of dose Q are needed to arrive at a saturation of $\Delta(nd)$. Only for a very low dose ($Q \simeq 10^{11}$ photons/cm^2) is the efficiency η of stored charge per absorbed photon of the order of unity; η then decreases exponentially as dose increases. We explain this new phenomenon as follows. In order to reach an available trap, the carriers have to traverse an already neutralized layer of space charge of width $\Delta x = \Delta(nd)/Z$, where Z is the volume density of deep traps which can retain the carriers (deep donors in the case of the substrate portion of the space charge). Therefore the differential buildup is

$$d\Delta(nd)/dQ = \gamma \exp(-\Delta x/L), \tag{1}$$

where the conversion coefficient γ describes the number of carriers available at the interface per number of photons. The mean free path L is given by

$$L^2 = \hat{\mu}(kT/q)\tau, \tag{2}$$

where $\hat{\mu}$ is the mobility in the space-charge region, k is the Boltzmann constant, T is the temperature, and q is the elementary charge. The lifetime τ is small in the space-charge region, since shallow negative acceptors capture holes very rapidly and shallow positive donors do likewise for electrons. These catpured particles then recombine—even across donor-acceptor separations exceeding 10^{-5} cm—by the neutral donor/neutral acceptor pair recombination (D^0, A^0) which is well known from luninescence spectra.[14]

Integration of Eq. (1) leads to the solution

$$\Delta(nd) = ZL\ln(1 + Q/Q_0) \tag{3}$$

with $Q_0 = ZL\gamma^{-1}$. The solid curve in Fig. 1 is a plot of Eq. (3) with a cutoff yielding a constant $\Delta(nd)$ at neutralization of the space charge with doses $Q \gtrsim 10^{16}$ photons/cm^2. The agreement of theory and experiment is excellent; the slope of the curve $\Delta(nd) = f(Q)$ in Fig. 1 is well described by $Z \simeq 4\times10^{16}$ cm^{-3} and $L \simeq 5\times10^{-6}$ cm (from hole mobility 100 cm^2/V s, $kT/q = 3\times10^{-3}$ V, $\tau = 10^{-10}$ s), yielding a slope ZL from Eq. (3) of 4.6×10^{11} cm^{-2} per decade of Q, as found also experimentally. The shallow interface of the sample and the chosen wavelength result in γ of the order of 0.5, thus $Q_0 \simeq 4\times10^{11}$ photons/cm^2, in agreement with the experimental curve in Fig. 1. The saturation occurs for $\Delta(nd)^{\text{sat}} \simeq 1.8\times10^{12}$ carriers/cm^2 in agreement with the known dopint of the interface; a small potential barrier of about 0.07 V, corresponding to about 25 kT/q, must remain to prevent carriers from spilling over to the opposite side of the interface, destroying PP.

Note that no arbitrary parameters are introduced in this quantitative explanation. The detailed investigations with variations in geometry, wavelength, and temperature also give good quantitative agreement, and they will be described elsewhere.[15]

Referring now to the electron Hall mobility curve of Fig. 1, we observe enhancements of μ by about 9% maximum, which fall to about 3% at saturation. The mobility μ is in our case determined by ionized impurity scattering. The density of ionized impurities in the layer does not change appreciably because the Fermi level is already close to the conduction band due to donor doping, and the neutralization of impurities by holes is only a short-lived transient in this n-type layer. Therefore we can relate changes in μ to changes in the average electron volume-density n via standard Brooks-Herring (BH) theory,[16]

$$\Delta\mu/\mu = A\Delta n/n, \tag{4}$$

because the free carriers screen the scattering Coulomb potential. The coefficient A is derived from BH theory: $A = Bb^2/(1+b)^2$, where $B^{-1} = \ln(1+b) - b(1+b)^{-1}$ and $b = \text{const}\ T^2n^{-1}$, with T being the temperature.[16] In our case, A is of the order of unity (for $n = 10^{17}$ cm^{-3}, $A = 1.2$ at 32 K). The observed mobility enhancements therefore yield the total electron density $n_0 + \Delta n$. The density enhancements calculated from the mobility values of Fig. 1 using Eq. (4) are maximal about 8%, and 2% at saturation. Most of the PP enhancement is thus *not* caused by an increase of carrier density (as is almost always claimed from conductance data), but rather originates largely from a widening of the conductive layer at the expense of an adjacent nonconductive space-charge region! The dashed mobility curve of Fig. 1 was used to calculate the electron density from it we could determine the widening $\Delta d/d$ of the layer (dotted curve).

The increase of the average electron volume density is greatest for low doses, then falls off. For low doses the electrons can be stored in the potential minimum near the layer center. This minimum flattens and rises upon further illumination and storage, and the electrons now move towards the layer edge, compensate the positive space charge, and widen the layer. We have thus separated both contributions, Δn and Δd, which would not have been possible by simple conductance measurements.

We have thus shown that a transient analysis with the Hall effect at photon doses below saturation is a novel and informative tool to investigate transport near semiconductor interfaces, especially in the regime of ionized impurity scattering and for the controversial persistent photoconductivity mode. Our studies establish the following general points. (i) Before an observation of PP can be related to postualted microscopic barriers near individual atomic recombination centers, one has to ensure that no macroscopic barriers exist which were here shown to cause PP. (ii) Conductance measurements and even Hall-effect data of thin layer structures with adjacent space-charge regions—which includes heterojunctions—ought not to be construed as yielding evidence for increases in carrier volume densities before one has reason to exclude changes in the geometry of the conducting layer. (iii) Systematic studies of the dose dependence of PP cannot only be utilized to measure photon doses but are also a powerful tool to characterize semiconductor transport near interfaces.

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