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Photocurrent diffusion length in disordered GaN

**A. Koo · F. Budde · B. J. Ruck · H. J. Trodahl ·
A. Bittar · A. R. H. Preston**

Abstract The diffusion length of carriers in semiconductors is a significant parameter determining the suitability of a material for device applications. Here we describe a simple new technique to measure diffusion length and apply it to a study of two types of disordered GaN. We find the diffusion length to be of the order of microns in nanocrystalline GaN and hundreds of microns in amorphous GaON. Experimentally the method involves the defocussing of a laser spot between two contacts. The results are supported by numerical modelling of the carrier concentrations in the experiment.

1 Introduction

Since the introduction of the steady state photocarrier grating technique (SSPG) [1] to measure the ambipolar diffusion length, this parameter has been widely used to characterise disordered semiconductors. In particular the ambipolar diffusion length, along with a measurement of the steady state photoconductivity, allows determination of the mobility lifetime product $\mu\tau$ of a-Si:H, a parameter which has been found to correlate with solar cell efficiency [2]. Measurement of the ambipolar diffusion length is important not only for a-Si, but is also a significant consideration in maximising efficiency of most semiconductor devices, including those based on III-Vs. Here we describe a new technique for measuring the diffusion length and apply it to the study of GaN.

The films studied for this work are nanocrystalline GaN (nc-GaN) and amorphous GaON (a-GaON) grown by ion assisted deposition. The preparation conditions and photoconductive properties have been described in previous papers [3–6]. The nc-GaN films are composed of stoichiometric 3 nm crystallites, with a band gap similar to that of crystalline GaN (3.4 eV), and exhibit photoconductivity at wavelengths shorter than the band gap. The a-GaON film has an oxygen concentration of 12 at. % replacing nitrogen; the band gap is blue shifted by 0.4 eV and the photoconductivity observed is persistent and much larger than that in nc-GaN.

2 Experiment

In contrast to SSPG wherein spatial modulation of the photogenerated carriers is introduced via interfering beams, we focus a single beam between parallel electrodes as shown in Fig. 1(a). If the film is moved up through the focussing cone (Fig. 1(b),(c)) the separation L between the region of high density of carriers in the illuminated region and the electrode is shortened. As this separation changes

A. Koo (✉) · F. Budde · B. J. Ruck · H. J. Trodahl ·
A. Bittar · A. R. H. Preston
MacDiarmid Institute for Advanced Materials and Nanotechnology, Wellington, New Zealand
e-mail: Annette.koo@csiro.au

A. Koo · F. Budde · B. J. Ruck · H. J. Trodahl
School of Chemical and Physical Sciences, Victoria University of Wellington, P.O. Box 600, Wellington, New Zealand

A. Bittar · A. R. H. Preston
Measurement Standards Laboratory, Industrial Research Ltd, P.O. Box 31310, Wellington, New Zealand

Present Address:
A. Koo
CSIRO Minerals, Box 312, Clayton South, VIC 3169, Australia

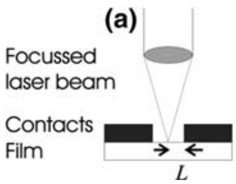

Fig. 1 Schematic diagram showing how L, the separation between the laser spot and electrodes changes as the film is moved through the focussing cone of the laser beam

from being longer than the diffusion length of photogenerated carriers to shorter, the photocurrent measured increases, allowing determination of the diffusion length.

In our experiment the diameter of the spot is 10 μm at focus. The gap between electrodes is 50 μm so the separation between the edge of the laser spot and the electrode is varied from 20 μm at focus to 0 μm. The current was monitored as a function of this separation with a potential difference of 9 V applied across the gap.

3 Results and analysis

The results of the focussing experiment are shown in Fig. 2 for nc-GaN and a-GaON. We can see directly from the plots that photocurrent is detected even when the separation is a significant portion of the gap, so the photogenerated carriers appear to travel several microns before recombination occurs.

To a first approximation, the data tell us that the apparent distance that carriers travel in the material is ~6 μm in the nc-GaN and ~100 μm in the a-GaON. For a more accurate estimate it is necessary to model the spatially varying densities of carriers.

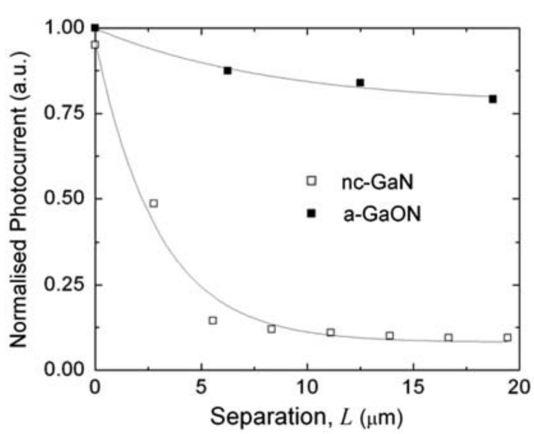

Fig. 2 Photocurrent versus separation between edge of laser spot and contact. The solid lines are guides for the eyes

3.1 Numerical modelling of the ambipolar equation

We begin our modelling by considering the schematic diagram of the illuminated spot and the electrodes shown in Fig. 3. The spot radius r varies from the minimum value $r_0 = 5$ μm obtained when the spot is fully focussed to $r = r_0 + \delta r = 25$ μm when the entire gap is illuminated, with a corresponding variation in L from $L_0 = 20$ μm to zero. The effective carrier generation rate G and electric field E depend on the spot size, as described below. We assume that the spot always acts as a partial short circuit, and that the current is limited by the concentration of carriers that diffuse into the unilluminated regions between the spot and the electrodes. Furthermore, we assume for simplicity that only those carriers generated closest to the electrodes (dark shaded regions in Fig. 3) give a significant contribution to the excess carrier concentrations outside the illuminated region. Finally, we make the assumption that the distribution of excess carriers varies only in the direction x shown in the diagram, while between the spot and the electrode it is uniform in the vertical direction. These assumptions are most valid when the spot size is such that r is always much larger than L, conditions which subsequent experiments could easily be designed to adhere to more rigorously.

A spatially varying generation of excess carriers in a semiconductor results in ambipolar transport in which the densities of excess holes (δp) and excess electrons (δn) are held together by the internal electric field induced when the carriers are separated by the external electric field. A pair of carriers travelling together is described as an 'ambipolar pair'. Under the assumptions described above a one-dimensional analysis is sufficient, in which case the steady state continuity equation for the ambipolar pairs, δn, is [7]:

$$D' \frac{\partial^2(\delta n)}{\partial x^2} + \mu' E \frac{\partial(\delta n)}{\partial x} + G - \frac{\delta n}{\tau} = \frac{\partial(\delta n)}{\partial t}. \tag{1}$$

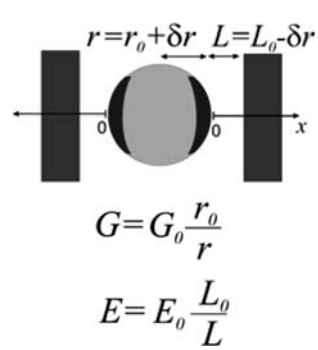

Fig. 3 Schematic of the laser spot between contacts, and determination of generation rate and electric field dependence on spot size

G is the generation rate of carriers, $\delta n/\tau$ is the recombination rate where τ is the recombination time, and E is the electric field in the films. D' and μ' are effective mobility and diffusion coefficients given by

$$D' = \frac{D_n D_p (n+p)}{D_n n + D_p p}, \quad \mu' = \frac{\mu_n \mu_p (p-n)}{\mu_n n + \mu_p p}. \tag{2}$$

n and p comprise both the dark and photogenerated densities.

For a point source of illumination at $x = 0$ and one dimensional transport the ambipolar pair density decays with an asymmetry that depends on the strength of the applied electric field and the magnitude of the ambipolar mobility.

We have modelled this situation numerically using a point illumination source and parameters that reflect the experimental conditions. The generation rate introduces a density of carriers much higher than in the dark and the recombination time is chosen so that the final distribution decays over microns as observed. Initial calculations used $\tau = 3 \times 10^{-5}$ s, $n_0 = 10^{12}$ cm^{-3}, $p_0 = 10^{11}$ cm^{-3}, $G(x = 0) = 10^{15}$ cm^{-3} s^{-1}, $E = -9/20$ Vμm^{-1}, $\mu_n = 10$ cm^2/Vs and $\mu_p = 0.1$ cm^2/Vs. D_n and D_p are found from μ_n and μ_p via the Einstein relation $D = \mu k_B T/e$ [7] with $T = 300$ K. The result is shown in Fig. 4. The effect of the applied field is enough to make the distribution asymmetric. It is the lower density in the positive x direction that limits the flow of current between the electrodes. It is important to note that the full nonlinear nature of Eq. (1) that results from the dependence of D' and μ' on n and p in Eq. (2) has been included in the numerical simulation. Our use of a one-dimensional analysis is significant here in that it greatly simplifies the solution of the nonlinear problem.

The experimental current-separation data will depart from the pattern implied by Fig. 4 in two respects, as illustrated in Fig. 3. First, since the illuminated area acts as a partial short circuit, the electric field increases as the size of the spot grows. Second, since we only consider the carriers generated closest to the electrode (dark shaded region in Fig. 3), then the number generated will decrease as the light is defocussed and the intensity at the edge drops. Thus as an aid to interpreting the data we have solved the equations numerically (i) at several values of generation rate while keeping the electric field constant, and (ii) at several values of electric field while keeping the generation rate constant. We then pick out the trends likely to influence the results as these parameters change with separation in our experimental data.

We will start by considering the effect of the drop in generation rate as the spot size grows. The generation rate is proportional to the intensity, which drops as $1/r^2$, and to the length of the region parallel to the contact, which grows as r. The generation rate $G(r)$ then varies as $1/r$.

At each value of L between 0 and 20 μm we calculate the distribution of ambipolar pairs $\delta n(x)$ with the generation rate set to $G = G_0 r/r_0$, where $G_0 = 2 \times 10^{15}$ cm^{-3} s^{-1} and $r = 25$ μm-L. These curves, shown in Fig. 5, then show the distribution of excess carriers measured from the edge of the illuminated spot. On each curve we denote the point at $x = L$ by a star, marking the location of the electrode. The curve traced out by the stars thus represents the current as a function of separation if the electric field across the gap were held constant.

It can be seen that the curve predicted under changing generation rate appears to have a longer persistence length than any of the calculated curves at constant intensity would suggest. To examine the effect of the parameter τ on this calculation we have chosen $\tau = 6 \times 10^{-5}$ s for the

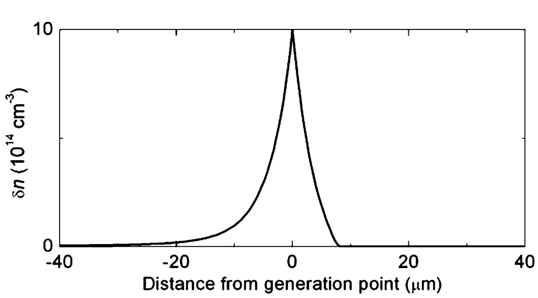

Fig. 4 Numerical solution to ambipolar equation with point generation source at $x = 0$ using parameters given in the text

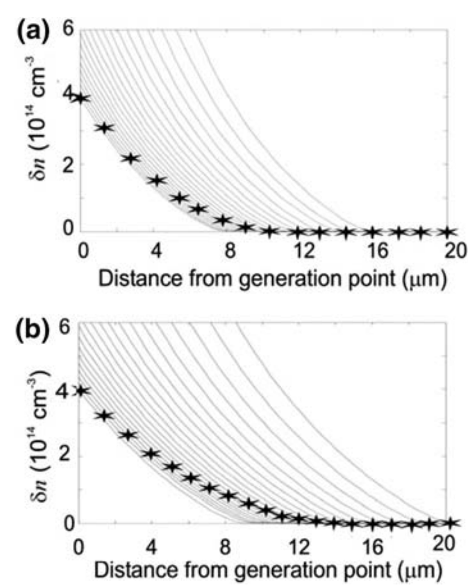

Fig. 5 Calculated density of carriers as a function of separation if generation rate varies as $1/r$ calculated at different generation rates for (**a**) $\tau = 6 \times 10^{-5}$ s and (**b**) $\tau = 12 \times 10^{-5}$ s. The stars mark the distance from the illuminated spot to the electrode

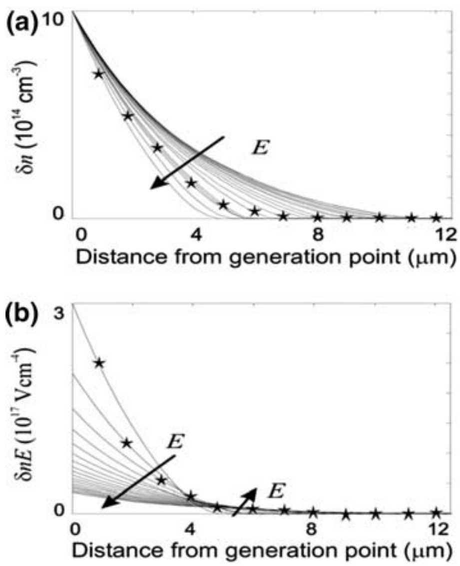

Fig. 6 Calculated (**a**) density of carriers and (**b**) δnE product as a function of separation if E is changing as $1/R$ (shown by stars)

calculations shown in Fig. 5(a) and in Fig. 5(b) we show the results for $\tau = 12 \times 10^{-5}$ s. The apparent length over which carriers can travel is slightly more exaggerated in the latter case.

The same process may be followed to see the effect of variation in the electric field with spot size. If the carrier density within the spot is much greater than that outside the spot, the spot will act as a short circuit and the field will increase as $1/L$ from its minimum value $E_0 = -9/20$ V/μm, as shown in Fig. 3. As in the first case, we calculate the distribution of ambipolar pairs at each value of L with $E = -9/L$V/μm. The curves in Fig. 6(a) show the effect of increasing the field on the distribution of carriers. The stars overlaid on the curves show the distribution of ambipolar pairs as a function of L. However the current drawn is proportional to δnE and this is shown in Fig. 6(b).

When the separation is small, the electric field is large and the current correlates with electric field. As the separation increases the density of carriers dominates the L dependence and the current actually decreases as the electric field is increased.

The results of the numerical calculations suggest that even if the electric field or generation rate varies strongly with spot size, the estimated diffusion length will be correct to within an order of magnitude. We conclude therefore that the effective diffusion length for a-GaON is hundreds of microns and for nc-GaN is a few microns. In the former case, this agrees with previous evidence from thermally stimulated conductivity measurements that the diffusion length is several times the gap width for a-GaON [6]. In the latter, it is interesting to note that the indicated diffusion length is orders of magnitude greater than the crystallite size of 3 nm, and therefore grain boundaries do not limit the diffusion in this material.

4 Conclusions

We have demonstrated a defocussing technique to determine the spatial dependence of the photocurrent in nc-GaN and a-GaON. Numerical solutions to the ambipolar transport equation have enabled us to estimate the effective diffusion length from the results. The experiment will contribute to the characterisation and optimisation of photoconductive materials.

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