Special effects of 3D diffusion of plasma waves : non linear photoreflectance signal

B. Forget, D. Fournier, Vitali Goussev

► To cite this version:

B. Forget, D. Fournier, Vitali Goussev. Special effects of 3D diffusion of plasma waves : non linear photoreflectance signal. Journal de Physique IV Proceedings, 1994, 04 (C7), pp.C7-151-C7-154. 10.1051/jp4:1994736 . jpa-00253265

HAL Id: jpa-00253265

<https://hal.science/jpa-00253265>

Submitted on 1 Jan 1994

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Special effects of 3D diffusion of plasma waves: non linear photoreflectance signal

B.C. Forget, D. Fournier and V.E. Gusev*

Laboratoire d'Instrumentation, Université Pierre et Marie Curie, ESPCI, 10 rue Vauquelin, 75005 Paris, France

** International Laser Center, Moscow State University, 119899 Moscow, Russia*

ABSTRACT: Increasing the photon flux of the pump beam can lead to non linearities in the photoreflectance signal of semiconductor samples. We will show that it is more difficult to obtain the non-linear regime in the case of three dimensional diffusion than in the monodimensional case. This observation adds credit to our model which assumes that non-linear effects observed are due to Auger recombination.

1. INTRODUCTION

Recently we have proposed a model based on Auger recombination in order to explain the non linearities in the photoreflectance signal obtained on silicon samples [1]. The proposed model considered only mono-dimensional diffusion. We have observed that focusing the pump beam in order to increase the incident photon flux was not always sufficient to reach the non linear regime. In this paper, we will show that changing from 1D to 3D diffusion equations renders the free carrier density (hence the plasma contribution to the signal) less dependent on Auger lifetime, therefore making it more difficult to observe non linear photoreflectance signal.

2. EXPERIMENTAL RESULTS

We made experiments using different objectives of the photothermal microscope [2] on an intrinsic Si sample in order to study the effect of focusing on the transition from linear to non linear signal. When we switch objectives from 5X (N.A. 0.1) to 20X (N.A. 0.4), the beam radius, a , is reduced by a factor four (for roughly 4 μm to 1 μm) and thus the incident flux ϕ is increased more than ten times.

We can see in figure 1 that with the 5X objective only the $\sqrt{\phi}$ dependence (which is the non linear plasma contribution) is reached while with the 20X objective we can observe the faster increasing thermal contribution (which is in $\phi^{3/2}$ in the non linear regime [1]). This is consistent with the increase in absorbed photon flux.

Figure 1 : Photorefectance signal for a modulation frequency of 500 kHz, as a function of pump power for two different microscope objectives, or pump beam size.

On the other hand, if we look at the transition from linear to non linear plasma contribution we notice it occurs nearly at the same power and not the same flux. Our first model is insufficient to explain this fact and we must now consider effects of 3D diffusion.

3. THREE DIMENSIONAL NON-LINEAR REGIME

Solving the 3D diffusion equation in the non linear regime can be quite troublesome. We have therefore developed a paraxial 3D model, valid for the quasi-stationary diffusion of free carriers (i.e. modulation frequencies lower than 1 MHz), which permits to express the condition for non linear signal as a function of incident power and beam radius independently. We obtain a result by imposing the following form to the solution of the carrier diffusion equation :

$$n(r, z) \equiv n_s g(z) \exp\left(-\frac{r^2 g(z)}{a_p^2}\right) \quad (1)$$

The free carrier density at the surface, n_s , is then found to be :

$$n_s = \sqrt{2} \frac{\phi}{\sqrt{\xi + \sqrt{\xi^2 + 2D\gamma\phi^2}}} \quad (2)$$

in which $\xi = \frac{8D^2}{3a^2} + \frac{D}{\tau}$, a being the pump beam radius, D the electronic diffusivity, γ the Auger coefficient and τ the recombination time associated with the Shockley-Read-Hall recombination process.

Considering equation (2), the free carrier density becomes non-linear when :

$$\phi \gg \frac{\xi}{\sqrt{2\gamma D}} = \sqrt{\frac{D}{2\gamma}} \left(\frac{8D}{3a^2} + \frac{1}{\tau} \right) \quad (3)$$

To analyse this condition (plotted in figure 2) we must consider two cases, defined by the dimensionality of the problem :

$$a \begin{matrix} > \\ ? \\ < \end{matrix} \sqrt{\frac{8}{3}} \cdot \sqrt{D\tau} \quad (4)$$

in which $\sqrt{D\tau}$ is the free carrier diffusion length and is typically a few hundred microns.

In the monodimensional diffusion case ($a \gg \sqrt{D\tau}$), expression (3) reduces to :

$$\phi \gg \frac{1}{\tau} \sqrt{\frac{D}{2\gamma}} \quad (5)$$

This expression defines a limit flux, which can be reached either by increasing the power, I , or by focusing the pump beam ($\phi \propto I/\pi a^2$) : consider point marked A in figure 2. Furthermore, since

$$n_s = \sqrt{\frac{\phi}{\sqrt{\gamma D/2}}} \quad (6)$$

it can be written that :

$$\tau \gg \frac{1}{\gamma n_s^2} \quad (7)$$

which states that non linearities in the signal appear when the probability of Auger recombination becomes larger than that of Shokley-Read-Hall (recombination probability is express by the inverse of the lifetime).

In the 3D diffusion case ($a \ll \sqrt{D\tau}$, which is the case for both experiments plotted in figure 1), the situation is quite different; equation (3) reduces to :

$$\phi = \frac{1}{h\nu} \frac{I}{\pi a^2/2} \gg \sqrt{\frac{D}{2\gamma}} \cdot \frac{8D}{3a^2} \quad (8)$$

There exists now a condition on the limit power, not on the flux, therefore independent of the radius of the beam :

$$I \gg \sqrt{\frac{D}{2\gamma}} \cdot \frac{4\pi}{3} \cdot h\nu \quad (8)$$

Consider point marked B in figure 2. Focusing the pump beam increases the photon flux and the density of free carriers generated, but the minimum density for non linear recombination to occur is also increasing. Focusing the pump beam in the 3D linear regime, while it still increases the free carrier density, cannot lead to the non linear regime.

Focusing the pump beam reduces the plasma diffusion length, and for a diffusion length much smaller than the one defined by the lifetime of free carriers, the effect of recombination on the free carrier density is reduced [3]. We are therefore comforted in our hypothesis that non linearities are due mainly to recombination processes : recombination being less determinant for tight focusing, it becomes more difficult (in the sense that a greater flux and thus a greater density of free carriers are needed) to observe non linear photorefectance signal.

Figure 2: The limit of inequality (3), which defines the passage from linear to non-linear regime, is plotted as a bold line. We can see that in the 1D regime (large radii, right part of the figure), the condition for non linear signal is flux dependant : reducing the radius by a factor 10 reduces the needed power by 100. On the other hand, it is power dependant in the 3D regime. Calculated with : $D=17 \text{ cm}^2/\text{s}$, $\tau=50 \text{ }\mu\text{s}$, $h\nu=2.4 \text{ eV}$ and $\gamma=4\times 10^{-31} \text{ cm}^6/\text{s}$.

4. CONCLUSION

We have expanded our non linear model to 3D geometry and made more precise the condition for which such non linear signal can be observed. This condition is coherent with our experimental results. The difficulty associated with the three dimensional non linear regime explains why non linear effects have not been brought to attention until quite recently. Changing the dimensionality in study of semiconductors by photothermal methods changes the nature of the plasma contribution to the signal and one can take advantage of this by comparing 1D to 3D experimental results.

References

- [1] B.C. Forget, D. Fournier and V.E. Gusev, *Appl. Phys. Lett.* **61** (19), 2341 (1992).
- [2] A. Rosencwaig, J. Opsal, W.L. Smith and D.L. Willenborg, *Appl. Phys. Lett.* **46**, 1013 (1985).
- [3] B.C. Forget, *Phys. Rev.*, to be published.