# A Physical Interpretation for Superlinear and Sublinear Photoconductivity in Amorphous Semiconductors

*Photoconductivity in Amorphous Silicon*

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***Abstract:*** A description of nonlinearities in photoconductivity of photoexcited carries in amorphous silicon is obtained in terms of quasi Fermi levels of electrons and holes. Separation of quasi Fermi level is taken as index for the level of excitation and in its term a transition is obtained in the properties of the semiconductor. At lower level of excitation when the semiconductor is dangling bond dominated, a superlinearity in photoconductivity with respect to generation rate is obtained whereas at higher levels of excitation the charges in the semiconductor are tail states dominated with a consequent sublinear photoconductivity can be observed. This explains the physics underlying variations in lifetime and photoconductivity in amorphous semiconductors. Experimental results are usually confined to a small range of excitation levels and may correspond to sublinear or superlinear behavior depending on the region probed.

***Index Terms*** **- Amorphous semiconductor, Photoconductivity, Quasi Fermi levels and Recombination.**

## I. INTRODUCTION

Variation of photoconductivity with intensity of light in amorphous semiconductors in general and amorphous silicon in particular has been extensively studied experimentally as well as theoretically [1-10]. Both transient as well as steady state photoconductivity experiments show a large variation in intensity exponent, $\gamma$, when photoconductivity is expressed as $\sigma_{ph} = G^{\gamma}$, $G$ being generation rate of carriers. This has been attributed mainly to the role of recombination at the dangling bonds which is highly intensity dependent and is dependent on the Fermi levels position. Most of these studies show that dangling bonds are the main recombination centers with very large capture cross sections compare to those for tail states [2, 11-13]. A model which emerges out of these studies is that recombination takes place at dangling bonds and the localized tail states are trapping centers. The procedure is simple in which the recombination rate at dangling bonds is calculated as a function of carrier concentrations while maintaining the charge neutrality condition [14]. Thus for a given value of free electrons the density of trapped electrons, free and trapped holes and charge density of dangling bonds is calculated for a neutral semiconductor and recombination rate for correlated dangling bond states is calculated accordingly. Since in a steady state condition recombination rate is equal to the generation rate the dependence of photoconductivity on light intensity can easily be explained.

Thus in this paper we aim to analyze properties of intrinsic amorphous silicon semiconductor with respect to level of excitation defined in terms of quasi Fermi levels. The analysis presented here also gives a new interpretation and firm theoretical basis to some of the results available in the literature [4].

## II. SEMICONDUCTOR WITH DANGLING BONDS

We start our calculations on the basis of the assumption that band tails do not contribute towards recombination, which is assumed to proceeds via dangling bonds. The main defects in the semiconductors are dangling bonds. We assume the two dangling bond states to have energy levels $E_1$ and $E_2$. The actual semiconductor differs from the ideal one mainly due to the presence of dangling bonds. Due to this change the Fermi levels in thermal equilibrium and quasi Fermi levels under excitation get modified. **Figure 1(a)** shows the variation of quasi Fermi levels for dangling bond density $N_{db}$ equal $10^{16}$ cm$^{-3}$ and $C = 100$, the ratio of charged and neutral trap cross-section ions. We have done these calculations for a single dangling bond density ($N_{db} = 10^{16}\ cm^{-3}$), as this is the usually reported order for the density of these states in a good quality hydrogenated amorphous silicon sample and ratios of capture cross-sections. The role of dangling bonds in amorphous semiconductor is therefore, not only in determining the recombination but also in modifying the quasi Fermi levels of electrons and holes.

As the level of excitation is increased the semiconductor tends to get itself free from the influence of dangling bonds. Thus in terms of excitation the semiconductor can be divided in two parts; for low level of excitation $E_{fn}$ , $E_{Fp}$ and carrier densities are determined by dangling bonds whereas at higher excitations the semiconductor behaves like an intrinsic semiconductor as far as charge distribution is concerned.

## III. SEMICONDUCTOR WITH OTHER DEFECT STATES

In the analysis so far we have considered only the effect of dangling bonds and have calculate Fermi level and quasi Fermi levels of a semiconductor free from all other defects. However some unintentional doping always exists in a semiconductor which tends to move the quasi Fermi level up or down. This is mainly due to presence of additional ionized impurities in the semiconductor.

The presence of these impurities moves the thermodynamic equilibrium Fermi level up and down. We consider here a case in which such impurities make the semiconductor slightly n type. In **Fig. 1(b)** we have assumed an impurity level so that $E_{f0} = 0.95\ eV$. As is clear from this figure the upward movement of $E_{f0}$ moves the transition from higher excitation level to lower excitation level. Thus the

role of impurities other than the dangling bonds is to move the level of excitation for the transition backward or forward depending on the nature and density of impurities. We find that shift is mainly due to a change in the density of neutral dangling bonds in thermal equilibrium. When $E_{f0}$ moves up the density of $D^0$ states reduces and quasi Fermi levels are shifted as shown in the **Fig.1**.

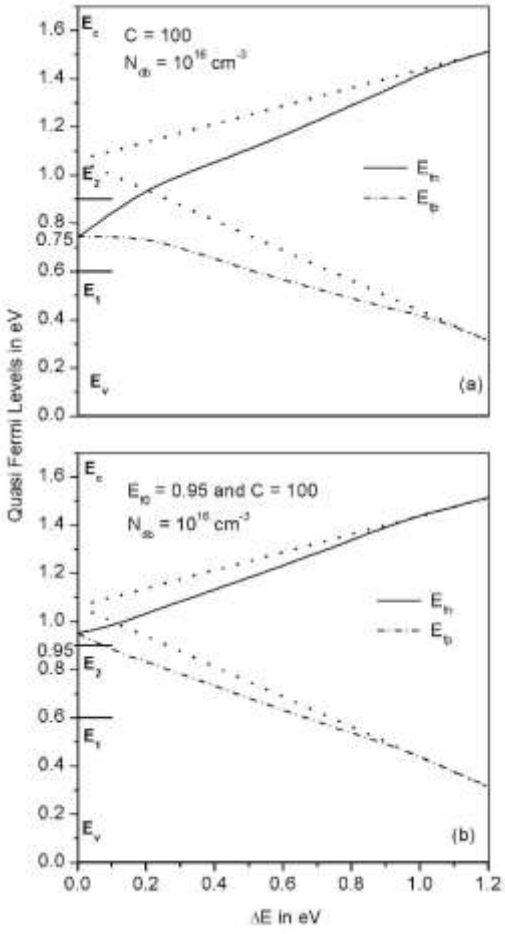


**Figure 1** Plot of quasi-Fermi levels $E_{fn}$ and $E_{fp}$ against $\Delta E = E_{fn} - E_{fp}$ by taking dangling bonds into account. **Fig. (a)** shows the curve for $E_{f0} \approx 0.75$ eV (without impurities) dangling bonds, whereas in **Fig. (b)** thermal equilibrium Fermi level $E_{f0}$ is taken at 0.95eV. Dotted lines show the quasi-Fermi levels for intrinsic case. . For the calculations $N_{db} = 10^{16}$ cm$^{-3}$and C =100 has been assumed.

The calculations presented so far reveal that in terms of level of excitation the semiconductor has two regions; one for low level of excitation in which defects and impurities determine $E_{fn}$ and $E_{Fp}$ and the other at higher level of excitation for which charge distribution is determined by the intrinsic properties of the semiconductor defined only in terms of density of states in the conduction band and valence band and in their tails. The transition is quite well defined and has important consequences in determining photoconductivity and carrier lifetime.

## IV. CALCULATION OF PHOTOCONDUCTIVITY

To understand the effect of variation in quasi Fermi levels on the properties of semiconductors, the calculated values of recombination rate and carrier concentrations $n$, $p$, $n_t$ and $p_t$ for various values of $E_{fn} - E_{Fp}$ are plotted in **Fig. 2** for $C = 100$ and $N_{db} = 10^{16}\, cm^{-3}$.

It remains for us now to correlate the above calculations with the experiments, in which the observable quantities are mainly generation rate $G$ (photon absorption rate) and the resulting photoconductivity, $\sigma_{ph}$. By assuming a uniform illumination one can assume constant quasi Fermi levels through out the sample and the electron and hole currents can be neglected. Thus in an ideal situation an equilibrium is achieved when generation rate is equal to recombination rate $R$. For this case electron concentration is given by,

$$(n - n_0) = G \cdot \tau \qquad (1)$$

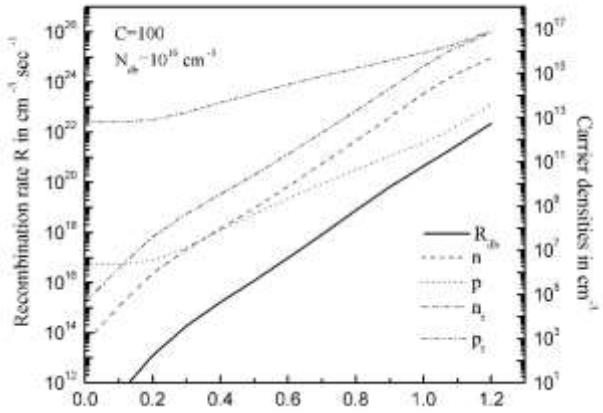


**Figure 2** Variation of recombination rate R and carrier densities *n, p, $n_t$* and *$p_t$* with ΔE for $N_{db} = 10^{16}$ cm$^{-3}$.

The photoconductivity of the semiconductor is given by

$$\sigma_{ph} = q\left[(n-n_0)\mu_n + (p-p_0)\mu_p\right] \qquad (2)$$

Here $n_0$ and $p_0$ is the density of free electrons and holes in thermal equilibrium respectively. However, for levels of excitation of interest for the numerical example we have taken here $n >> n_0$ and $n >> p$. All the other parameters for semiconductor are same as taken by Dhariwal and smrity, 2006 [14]. Thus for the semiconductor under study the photoconductivity is mainly determined by *n* and its lifetime. The photoconductivity and generation rate calculated from the above equations have been plotted in **Fig. 3(a)** for various values of dangling bond densities.

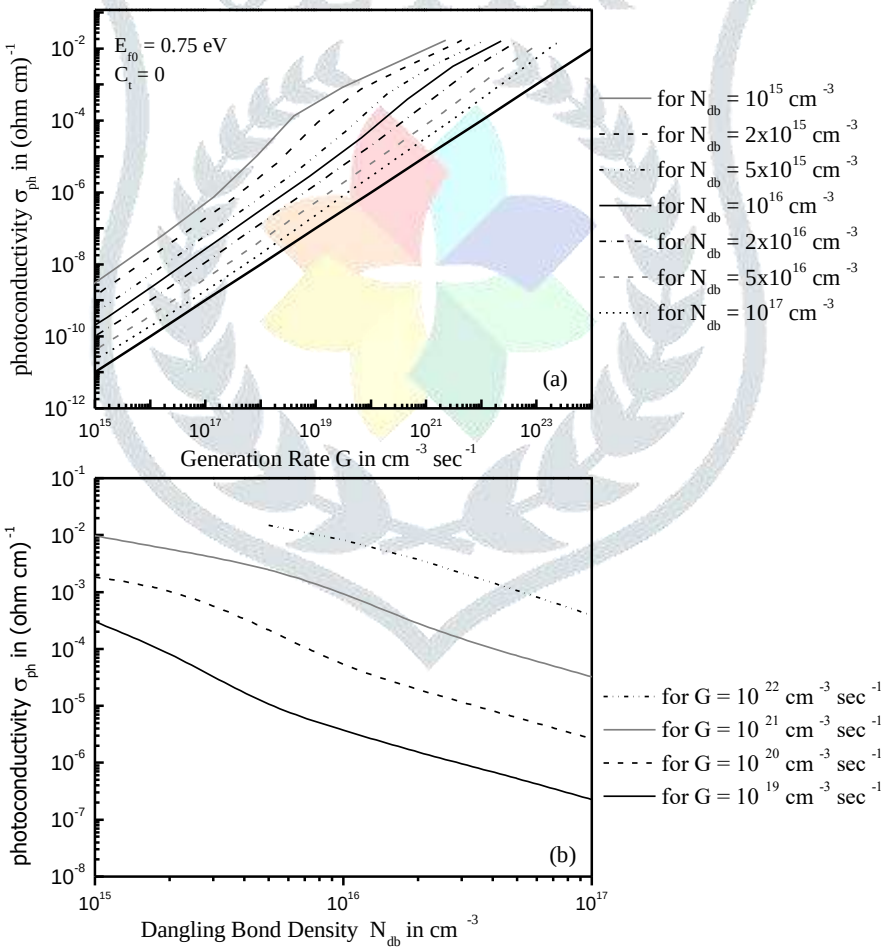


**Figure 3** Figure (a) shows the photoconductivity $\sigma_{ph}$ as a function of generation rate G at different values of dangling bond densities by assuming *$E_{f0}$=0.75 eV*. The dark line shows linear variation with the slope m = 1. Figure (b) shows variation of photoconductivity $\sigma_{ph}$ with dangling bond densities $N_{db}$ at various values of generation rate.

A superlinearity of photoconductivity is obtained for lower parts of the curves corresponding to the defect determined region, whereas the slope changes to sublinear dependence as semiconductor attains its intrinsic properties. These nonlinear variations of photoconductivity with generation rate may have serious consequences when light induced degradation [15-16] of a material is studied. In these studies the loss of photoconductivity is usually assumed to be directly dependent on dangling bond density ( $\sigma_{ph} \sim N_{db}^{-1}$ ). In

**Fig. 3(b)** we have plotted photoconductivity as a function of dangling bond density at various generation rates and find that due to the above mentioned superlinear behavior the decrease in photoconductivity with increasing density of dangling bond is much faster than expected. Typically the photoconductivity reduces by almost three orders of magnitude whereas the dangling bond density increases only by about two orders of magnitude. In any case the loss of photoconductivity cannot be used directly to determine the increase in dangling bond density.

A more appropriate procedure for such an analysis is to use variable intensity probes and study $(\sigma_{ph}/G)$ as a function of *G*. This will show maxima similar to those for life time τ. In figure 4 we have plotted $(\sigma_{ph}/G)N_{db}$ as a function of G for various values of dangling bond densities $N_{db}$. We have taken $(\sigma_{ph}/G)N_{db}$ instead of $(\sigma_{ph}/G)$ to bring all the curves on the same scale. However for practical studies it is sufficient to plot $(\sigma_{ph}/G)$. We find that the $(\sigma_{ph}/G)$maxima shift to higher values of G for higher densities of dangling bonds.

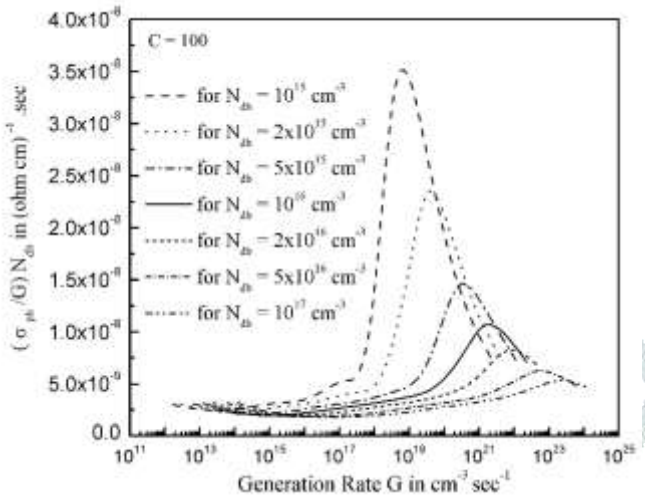


**Figure 4** $(\sigma_{ph}/G)N_{db}$ as a function of G at different values of dangling bond densities for $E_{f0}$=*0.75 eV*.

## V. Summary and Conclusions

To conclude we have presented a model for the calculations of photoconductivity and other related parameters of intrinsic hydrogenated amorphous silicon. Results have been obtained in terms of quasi Fermi levels of electrons and holes assumed to be common for free and tail states. Separation between quasi Fermi levels has been taken as index of level of excitation. For a truly intrinsic semiconductor the Fermi level is pinned at the center of dangling bond levels. Due to impurities thermal equilibrium Fermi level may move up or down and this will also affect the level at which the above said transition occurs. From our calculations we find that for an intrinsic semiconductor light induced degradation experiments give misleading results if are based on photoconductivity measurements at a fixed generation rate. It is true only for very low intensities. This is clear from figure 4 in which all the curves tend to merge together only at very small generation rates.

We find a strong correlation between transition from superlinearity to sublinearity in the photoconductivity and the transition from dangling bond dominated to intrinsic (tails dominated) semiconductor. This result is in agreement with the theoretical calculations of Bube et al. [4, 5], who have observed a similar shift in photoconductivity in terms of generation rate as the Fermi level position is changed. We obtained the same result in terms of the excitation level and transition of quasi Fermi levels. Thus our calculations provide a physical interpretation to prediction made by Bube et al.

It is important to note that the excitation level Δ*E* represents the separation between the quasi Fermi levels of electrons and holes and for devices like solar cell made of such materials [17] corresponds to an excitation voltage *V* which is equal to the terminal voltage under the open circuit condition and the flat band approximation. Thus the calculation of quasi Fermi levels and their transition should be viewed in terms of the device physics.

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