A Transient Analysis for Amorphous Photoconductors

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Abstract. The study has been carried out for the transient response of photosensors fabricated by amorphous semiconductors under variable levels of excitation when switched off from steady-state. The curves for the entire range of the transient have been plotted in the terms of photoconductivity and they can be converted to current decay curves by multiplying with the applied electric field and the cross-sectional area of the sample. For this purpose, in the calculations, the transit time effect is included. Also, the switching time and gain of the photoconductor have been calculated. It is found that the current gain of the device increases as the density of thermal equilibrium electrons is made higher, compared to that of holes by moving the Fermi level upward. However, this also increased the switching time and its performance, as a switch becomes poorer.

1. Introduction
Optoelectronic devices based on amorphous semiconductors can be divided in two categories, photodetectors (photosensors) and photovoltaic converters. The photodetectors are also of two types: photoconductors and photodiodes [1].

The photoconductors are photodetectors with a photosensitive material on which two ohmic contacts are made to allow current to flow in proportion to the photoconductivity. On the other hand, photodiodes use rectifying contacts which allow the separation of charges created by the optical signal.

In this paper, a study has been made for the transient response of photoconductors, when switched off from steady-state. These properties give information about the fundamental processes in the material and are of great practical interest because of their applications as image sensors. Shen and Wagner [2] have analyzed, transient photoelectric characteristics for amorphous silicon photodetectors and they compared their results for two types of photodetectors, the photoconductor and photodiode. In either of these devices, the image processing requires fast switching and therefore the transient response becomes important.

2. Photoconductors: Transit and Switching time
Photoconductors or photoconductivity cells are based essentially on the properties of bulk semiconductors on which ohmic contacts are provided for measurement of variations in conductivity, with respect to change in light intensity. Here, a planar geometry is assumed in which the semiconductor is uniformly illuminated and contacts are at the two ends of a photoconductor. By assuming a unit area of the cross-section for a generation rate G and an applied voltage V across the photoconductor the current through it is given by,
Here $E$ is the electric field, $V_d = V_{bi} + V$ is the drift voltage across the $i$-layer which has a built-in potential difference $V_{bi}$ and $w$ is the width of the intrinsic layer [3]. The photoconductivity of a semiconductor is given by,

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

$$= q\left(\mu_n\delta n + \mu_p\delta p\right)$$

where $n_0$ and $p_0$ are the carrier densities in thermal equilibrium. The electron-hole pairs generated by photons with intensity $G$ will give a primary current per unit area, as

$$J_G = Gw$$

The current gain of the photoconductor is defined as a ratio of $J_{ph}$ and $J_G$ and is given by,

$$G_{ph} = \frac{J_{ph}}{J_G} = \frac{\sigma_{ph}V_d}{qGw}$$

or,

$$G_{ph} = \frac{\sigma_{ph}V_d}{qGw^2}$$

If the semiconductor is slightly n-type as in the case of amorphous silicon, the photoconductivity can be approximated as,

$$\sigma_{ph} \approx q\mu_n\delta n$$

and thus we have,

$$G_{ph} = \frac{\mu_n\delta nV_d}{Gw^2}$$

Further by noting that in steady-state the rate of generation is equal to the rate of recombination, we can write

$$\delta n = G\tau$$

where $\tau$ is the effective lifetime of electrons at that level of injection. Thus in the steady-state condition

$$G_{ph} \approx \frac{\mu_nV_d\tau}{w^2} \approx \frac{\tau}{\tau_t}$$

where

$$\tau_t = \frac{w^2}{\mu_nV_d}$$

is the transit time of the photoconductor.

The response (switching) time of a photoconductor can be defined as the time when the current drops to 10% of its steady-state value when the light is switched off. For a typical amorphous silicon intrinsic layer photoconductor with the parameters used in [3], current densities have been plotted in figure 1 against time for a 1μm thick photoconductor when a potential difference of 1volt exists across it.

In table1, the calculated gain for different values of generation rate $G$ and Fermi level $E_f$ have been shown. It’s found that the gain of the photoconductor is less at a higher level of excitation, which means that the proportionality between output current and intensity of light is sublinear with respect to
photoconductivity [4]. The $\mu\tau$ product is calculated for steady-state and for an assumed value of $\mu$ (assuming electrons to be the main carriers), the steady-state lifetime, $\tau$, has been determined. From the curves of current densities, one can find out the switching (off) time, $\tau_s$, of the photodetector, as the time when gain has reduced to 10% of its original value. Ordinarily, this time should be nearly equal to $2.303\tau$. However, a much longer value of $\tau_s$ is observed. This is due to the release of the charge stored in the tail states. For seeing the effect of increment in dangling bond density on the current density decay, photocurrent and photoconductivity curves are plotted as a function of time for $N_{db}=10^{17}$ cm$^{-3}$ and $G=10^{21}$ cm$^{-3}$/sec$^{-1}$ in figure 2 and results of these calculations are also given in table 1. It’s been found that with the increment in dangling bond density the gain and switching time reduces.

**Figure 1.** Transient photocurrent density $J_{ph}(t)$, for dangling bond density $N_{db}=10^{16}$ cm$^{-3}$ (a) for $G=10^{21}$ cm$^{-3}$/sec$^{-1}$, (b) for $G=10^{20}$ cm$^{-3}$/sec$^{-1}$.

**Figure 2.** Transient decay curves for $N_{db}=10^{17}$ cm$^{-3}$ and $G=10^{21}$ cm$^{-3}$/sec$^{-1}$ (a) Photoconductivity, $\sigma_{ph}$, (b) Photocurrent density $J_{ph}(t)$.

**Table 1.**
The decay in electrons and holes concentration amounts to the collapse of quasi-Fermi levels and their tending to the thermal equilibrium value $E_{\text{f0}}$. The variations of the quasi-Fermi level of electrons and holes with time for three values of $E_{\text{f0}}$ and $G = 10^{21} \text{ cm}^{-3} \text{sec}^{-1}$ are shown in figure 3. It should be noted that in the case of transients only the free carrier concentrations $n(t)$ and $p(t)$ can be described by these time-dependent quasi-Fermi levels and the trapped electron and hole densities in the tail states [4] cannot be assigned these levels. That is, in case of transients a common quasi-Fermi level cannot be defined for the free and trapped electrons (or holes).
3. Discussion and conclusions

In this paper, the theoretical understanding of the transient behaviour of amorphous semiconductors is applied to electronic devices of practical interest. These materials can be used to fabricate devices to work either as photodetectors or energy converters [5].

From the analysis of current due to photoconductivity decay, it’s been found that the entire transient can be studied in different parts arising due to different operational mechanisms, e.g., for the study of the dominant recombination processes one should explore the initial part of the decay curve typically up to a few micro-seconds. As the time proceed one may observed humps in the decay curve arising due to re-emission of electrons and holes from the trap levels lying around quasi-Fermi levels of electrons and holes in the tail states. These humps can therefore be explored to obtain the density of states around Fermi levels. Further, the decay in the range of milli-seconds becomes linear on the log-log scale to which can be attributed a power-law decay. Thus the study of transients in photoconductivity cells gives very detailed information about the properties of the tail states and the dominant recombination mechanism.

By the analysis of variations in gain and off time, it’s been concluded that the current gain of the photoconductivity cell increases as the Fermi level moves up from the center of the dangling bond states (0.75 eV). Thus, higher values of $E_f$ result in a better current gain. However, the switching time, $\tau_s$, of the photoconductor used as detector also increases substantially resulting in a poorer switching performance. Here the switching time, $\tau_s$, of the order of nanoseconds obtained for the steady-state.
Thus, a model for transient response of amorphous devices of interest has been successfully developed. The theory may find useful applications in the interpretation of data obtained from the transient response of these devices.

References
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