Photoconductivity: A Tutorial on Fundamentals, Applications and Typical Photoconductive Materials

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***Abstract* — The purpose of this tutorial is to provide an overview of photoconductivity from basic principles to some advanced concepts. Photoconductivity definitions are introduced and the importance of electrical contacts are highlighted. The continuity equation platform is emphasized as a means of describing the photoinjected carrier dynamics in semiconductors with some simple solutions as examples. Photoconductivity experiments have been extensively used by numerous researchers to characterize semiconductor materials. The tutorial will address some typical photoconductivity experiments such as ac photoconductivity and time-of-flight (TOF) transient photoconductivity techniques. Selected examples of photoconductive materials are also considered for use in detectors for infrared to high energy radiation (x-rays).**

Keywords—photoconductivity; electrical contacts; continuity equation, steady state photoconductivity; transient photoconductivity; photoconductivity configurations; time-of-flight photocurrent

In many textbooks, the photoconductivity $\Delta\sigma$ is defined as the change in the conductivity of a semiconductor sample upon illumination, and is typically quoted through the well-known equation

$$\Delta\sigma = e\mu_e\Delta n + e\mu_h\Delta p \qquad (1)$$

where Δn and Δp are the photogenerated (or excess) concentrations of electrons and holes, and μ_e and μ_h are the electron and hole drift mobilities, which are assumed to be unaffected by illumination (or by Δn and Δp). The photoconductivity problem therefore boils down to finding Δn and Δp. Equation (1) appears to be a straightforward and simple equation but it has several major tacit assumptions that need to be highlighted and examined.

The fist step in understanding the results of photoconductivity experiments is to realize the importance of electrical contacts to the semiconductor. Electrical contacts are of central importance in the response of the semiconductor to illumination. The tutorial will show that ohmic or injecting contacts lead to *photoconductive gain* but noninjecting contacts allow space charges to develop within the semiconductor, and there is no photoconductive gain. The *Ramo-Shockley theorem* is introduced to relate the photocurrent to the drift of the photogenerated carriers; and also to relate the collected charge to the number of electron and hole pairs that are photogenerated.

The photogeneration, denoted by $g_{ph}(x,y,z,t)$, in general, has both time (t) and spatial (x,y,z) dependence. The time-dependence of photoconductivity experiments can be divided into three categories.

(a) DC photoconductivity
(b) Steady state photoconductivity
(c) Transient photoconductivity

In addition, we need to consider the spatial dependence of $g_{ph}(x,y,z,t)$, which leads to what are known as *photoconductivity configurations*. Two typical photoconductivity configurations are:

(A) Coplanar electrodes; the electrodes are on the same side of the semiconductor as the photoexcitation. Put differently, the photogeneration is perpendicular to the applied field
(B) Transverse electrodes; the electrodes are on the opposite sides of the semiconductor and the illumination is normally trough one of the electrodes, or such that photogeneration is between the electrodes. As distinct from A, the photogeneration is along the applied field.

There are other possible configurations as well, though the above two tend to be among the most common. In all cases, the problem of predicting the observed photocurrent density $j_{ph}(t)$, and hence the photoconductivity $\Delta\sigma(t)$, can be tackled by solving the continuity equation. The *continuity equation platform* involves solving the following set of equations solved simultaneously

(1) The continuity equation for photoinjected carriers under a defined photogeneration rate $g_{ph}(x,y,z,t)$

(2) Rate equations for trapping and release for each set of localized states in the bandgap (or mobility gap)
(3) Rate equations for recombination for each type of recombination process
(4) The Poisson equation, that is, Gauss's equation in point form

The above equations in (1) to (4) have to solved subject to initial and boundary conditions, given $g_{ph}(x,y,z,t)$

Analytical solutions are only available for simple cases, and these will be described during the tutorial. Most practical solutions rely on numerical solutions of the continuity equation. One can also use Monte Carlo simulations but such simulations are inherently slow because a large number of carriers have to be tagged and tracked through their transit across the sample to avoid large fluctuations (noise) in the results.

While most photoconductivity experiments involve monitoring the photocurrent in the external circuit, it is also possible to carry out photoconductivity experiments under open circuit conditions. Thus, in addition to the categories above, we need to introduce two more classifications:

(C) Short circuit photoconductivity configuration where the photocurrent flowing in the external "short circuit" is monitored (the bias voltage supply is treated as short for transient signals). An alternative statement of this condition is that the integration of the electric field E across the sample at any instant is constant and equal to the applied bias V_o.
(D) Open circuit photoconductivity configuration where the photocurrent flowing in the external "open circuit" is zero; the open circuit voltage $V(t)$ and its rate of change are monitored. An alternative statement of this condition is simply $J_{ph(}t) = 0$

C and D above must be incorporated into the continuity equation platform. Most experiments fall into the category (C) above. However, open circuit experiments have one distinct advantage that $J_{ph(}t) = 0$, and this condition introduces a useful simplification in the continuity equation platform in (1) to (4) above.

One particularly important case is the *time-of-flight* (TOF) *transient photoconductivity* experiments in which the sample is sandwiched between two electrodes, one of which is semitransparent. The photoexcitation is a highly absorbed very short light pulse that generates electrons and holes near the semitransparent electrode. The photocarriers that have the same polarity as the semitransparent electrode drift through the sample and generate a photocurrent $j_{ph}(t)$ in the external circuit. The measured signal is $j_{ph}(t)$. As the photocarriers drift, they interact with traps (localized states) in the sample. They become captured into localized states and later released back into the transport band. Further, some photocarriers can be lost into deep traps and cannot contribute to the photocurrent. The time dependence of $j_{ph}(t)$ can provide useful information on the photocarrier transport dynamics. As soon as the drifting carriers reach the collecting electrode, there is a sharp drop in the photocurrent $j_{ph}(t)$, which defines a *transit time*, from which one can determine the effective drift mobility of the photoinjected carriers. The shape of the photocurrent $j_{ph}(t)$ in TOF measurements can be used to extract valuable information on the density of localized states in a semiconductor sample. Some typical case studies for selected materials are shown and discussed.

The tutorial will also look at some popular photoconductors such as amorphous selenium alloys, HgI_2, HgCdTe diamond films, and use these as examples during the development of the principles above.

The tutorial will concentrate mainly on nondispersive transport and small signal excitation. Nondispersive transport refers to the transport of photoinjected carriers through the semiconductor in which the carriers reach a steady state, or quasiequilibrium, with respect to localized states before they reach the collection electrode. Put differently, there is a clear delineation (demarcation) between shallow and deep traps and this demarkation does not change during the time scale of the experiment. In dispersive transport, however, the distribution of localized states is such that the photoinjected carriers interact with deeper and deeper localized states as they drift so that they never actually reach a steady state behavior. The photoinjected carrier concentration is time dependent and photocurrent exhibits a monotonic decrease with time. The rate of decrease in the photocurrent sharply accelerates when the carriers begin to reach the collecting electrode. The transit time and the drift mobility determined from such measurements depend on the time scale of the experiment; that is, the drift mobility depends on the sample thickness.

The majority of the work in the past has been done under small signal conditions, that is, the photoinjected charges do not perturb the applied field. The field is assumed to be constant. There are many practical applications in which this is not the case, and the photoinjected carriers perturb the field. Some selected examples will be shown to highlight how the TOF photocurrent waveform depends on the photoinjection ratio r, that is, the ratio of photoinjected charge density to the charge density on the electrode. (Charge density here is a surface density). The importance of r is highlighted. Various experimental artifacts that can affect TOF measurements are also discussed.