Haynes-Shockley Experiment

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8 December 2004

The Haynes-Shockley experiment was first performed in 1951 as an illustration of minority carrier transport. It used an electric field containing an aligned, elongated bar of uniform cross-section, composed of n-type semiconductor material, capped at each end with a region of p-type material. The junction so formed at one end (the “emitter”) was forward-biased with either a constant or pulsed voltage, thereby injecting minority carriers (holes) to the n-material, where they were swept along under influence of the field. The mobile carriers were extracted and sensed at the other end (the “collector”).

A similar setup has been used to find, by experimental method, the minority carrier drift mobility and diffusion coefficient of a doped semiconductor.

The arrangement has also found variations popular in lab and demonstration courses. The source of charge carriers could be electrical, optical, or thermal excitation. With a long bar, sufficient charge injection, and proper detection, the two primary modes of semiconductor carrier transport – drift and diffusion – are separable. The basic elements of source, path, field, and detector can be implemented in hardware or modeled with software tools.

Here, a setup using optical excitation is simulated using Microsoft Excel/Visual Basic for Applications. The software components are:

(1) worksheets with cells containing supplied and calculated values that represent physical parameters, with column spaces that perform array calculations and store the results, and with a minimal set of user interface features

(2) program code modules that receive triggers from the user interface, construct an array representing an independent variable determined by conditions set in a worksheet, and populate a worksheet column space with the array

(3) scatter plots of the calculated array vs. the independent variable

The supplied parameters include: length of the semiconductor sample, end-to-end voltage, number of injected carriers per unit area, and number of data samples. The material is assumed to be n-type silicon at room temperature, so known values for mobility and diffusion coefficient are also supplied. (A trivial calculation could be added to obtain one from the other, to enable modeling for different materials.) The worksheet is set for continuous calculation, so intermediate scalar values for electric field strength and drift velocity are available.

The static simulation operates in two modes:

(1) Space distribution of charge for a fixed value of elapsed time since carrier injection

(2) Time distribution of charge for a fixed value of distance from the charge injection site

For the space distribution, an additional supplied value is the fixed value of time elapsed. The worksheet uses this value, together with the calculated drift velocity, to determine the distance traveled by the center-of-pulse from the injection site. (This models the drift mobility aspect of charge transport.)

For the time distribution, an additional supplied value is the fixed value of detector distance from the injection site. The worksheet uses this value, together with the calculated drift velocity, to determine the time at which the center-of-pulse reaches the detector. (This models the drift mobility aspect of charge transport.)

On receiving the "start" trigger, the worksheet and VBA code first determine a linear (space or time) distribution of sample points on either side of the center-of-pulse. (This models the diffusion feature of charge transport.) Then, according to the length of the bar and the position of the distribution, "filler" sample points are determined on either side of the distribution. The independent variable array is constructed and written to a worksheet column, which automatically calculates the dependent variable (charge density) array.

The result is a pair of arrays representing "x" and "y" on a scatter plot. (At present, the straightforward but time-consuming task of automating the graph production has not been finished, so the graph has to be built manually using the Excel interface features.)

The distribution of charge in the bar, a function of both time and distance, is governed by a second-order partial differential equation that accounts for the charge-diminishing effect of carrier recombination.

$\partial \delta p / \partial t = Dp * \partial^2 \delta p / \partial x^2 - \delta p / \tau_p$ Diffusion Equation

Other simulations have included recombination, by including the second term of this equation, to show the collapse of the charge distribution as it travels through the bar.

http://jas.eng.buffalo.edu/education/semicon/diffusion/diffusion.html

http://www.benfold.com/sse/hs.html

In a setup used to determine diffusion coefficient, however, the height of the traveling and dispersing pulse should be a simple function of time – charge should not disappear appreciably during the measurement interval. Therefore, the carrier lifetime should be long compared with the time of transport – which means that recombination effects should be negligible.

Eliminating the second term (recombination) leads to a simplified differential equation whose solution is a Gaussian distribution:

$\delta p(x, t) = P e^{-(x^{\wedge}2 / (4 * D_p t))}$ where $P = \Delta P / (2 \sqrt{[\pi D_p t]})$ is the max height of the distribution.

Calculating the mobility is straightforward. (See slides.)

If one could "snapshot" the spatial distribution at a known time after the injection, then the pulse height and width could be used to find the diffusion coefficient. (See slides.)

REFERENCES

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