

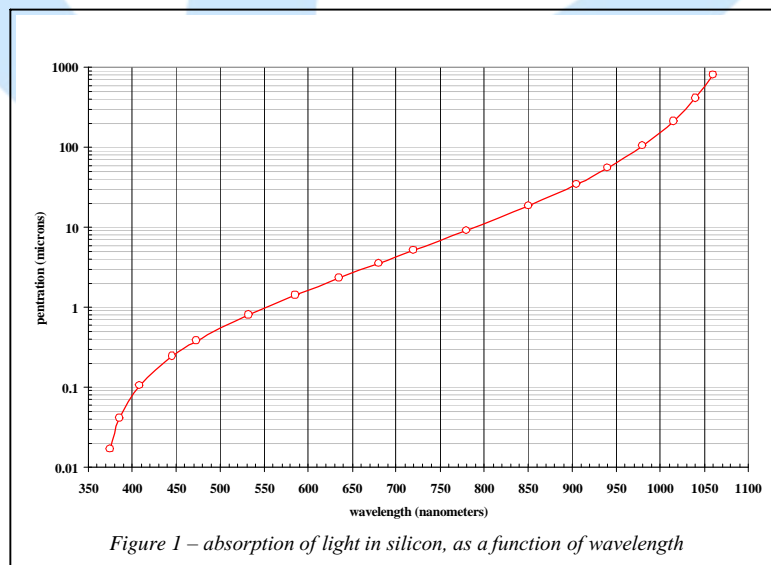
## Theory of SPV for Measuring Diffusion Length

SPV is an acronym for Surface Photovoltage, a phenomenon known for more than 50 years.<sup>1</sup> When light hits a semiconductor, excess holes and electrons are created, and minority carriers at the surface increase, changing the voltage at the surface.

The SPV phenomenon is used for many purposes, but most commonly the term is used to refer to a way to measure diffusion length, first proposed in 1961 by A.M. Goodman at RCA Laboratories.<sup>2</sup> While the measurement of diffusion length, via SPV, readily falls out of the equations describing surface photovoltage, before showing the math, it is helpful to create an intuitive explanation.

Although the theory of using SPV to measure diffusion length works for all types of semiconductors, the discussion will be simpler if we assume a piece of thick silicon whose top surface is in depletion, *i.e.* a region depleted of majority carriers. Since bulk silicon is electrically neutral, the depletion region has a net charge opposite in sign to the charge of the majority carriers. There is an electric field in the depletion region, forcing minority carriers to the surface. Thus, in p-type silicon the majority carriers are holes, the charge in the depletion region is negative, and the electric field in the depletion region forces electrons to the surface, creating a surface photovoltage.

Light falling on a semiconductor is absorbed, and the rate of absorption depends on the wavelength of light, as shown below, where the penetration is the depth at which the light intensity falls to 1/e times its initial intensity.



Note that shorter wavelengths are absorbed more quickly than longer wavelengths. In silicon, when the wavelength of light is shorter than 1.13 $\mu\text{m}$  (infrared), one photon creates one hole-

<sup>1</sup> W.H. Brattain, J. Bardeen, Bell Syst. Tech. J. 32 (1953) 1.

<sup>2</sup> Alvin M. Goodman, Journal of Applied Physics, vol 32, No. 12. Dec 1961

electron pair. The excess carriers created in the bulk silicon drift in what appears to be random motion, even though the net movement is from an area of greater concentration to an area of lesser concentration. Assuming the silicon is thick, some carriers drift away from the light and penetrate further into the silicon, and we can neglect those carriers. Other carriers, may drift into

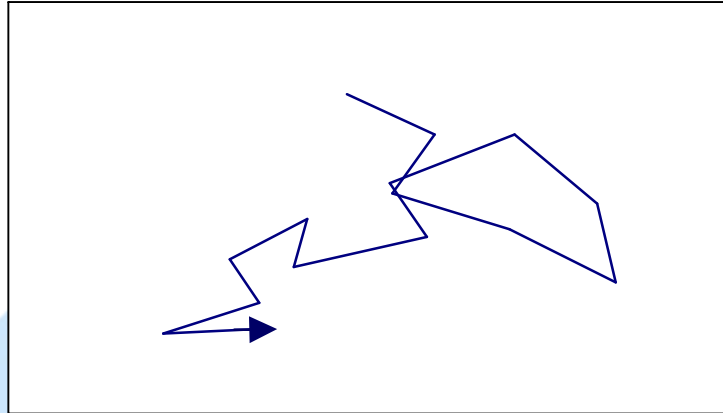


Figure 2 - apparently random drift motion of carriers

the depletion region. Minority carriers that enter the depletion region (or are created in the depletion region) are swept to the surface by the electric field, and create a surface photovoltage. This SPV signal can either be detected capacitively, when the light beam is chopped, or via an infinite impedance voltmeter, when there is a single change in light. The common technique is to use chopped light and detect the SPV signal capacitively.

Minority carriers that drift around in the bulk either eventually recombine with majority carriers, or they reach the surface, where they produce a surface photovoltage. The statistical distance that carriers travel in the bulk before they recombine (assuming that they do not get into the depletion region) is the diffusion length.

Thus, some minority carriers in the bulk do not make it to the surface to form a surface photovoltage. They recombine before they get there. The shorter the diffusion length, the less likely minority carriers will make it to the surface to cause surface photovoltage.

Longer wavelength light penetrates deeper into silicon than short wavelength light. Therefore, if we compare the SPV signal produced by pulses of two different wavelengths of light, each containing the same number of photons, then the longer wavelength will penetrate more deeply into the silicon, the minority carriers created will be more likely to recombine before they reach the surface, and the longer wavelength light will produce a smaller SPV signal than the short wavelength light. One can determine the diffusion length by comparing these two situations, as follows.

If we plot the light flux,  $\Phi$ , divided by the SPV signal,  $V_{SPV}$ , for each wavelength, as a function of the penetration depth into silicon of that wavelength, the result is a straight line whose Y intercept tells the diffusion length. (The X-axis is  $1/\alpha$ , the penetration depth for each wavelength of light used.)

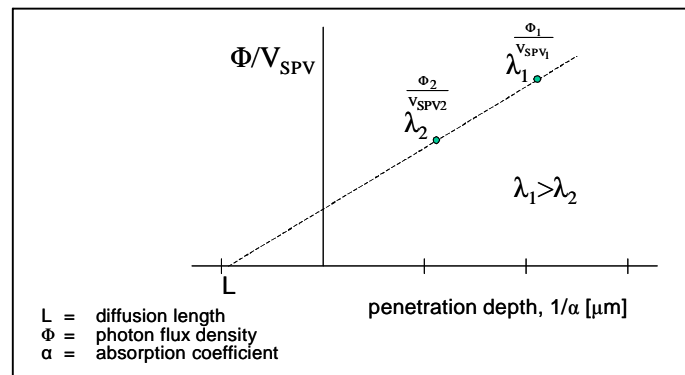


Figure 3 – graphical calculation of diffusion length via SPV signals

A variation on the method just described, *i.e.* holding  $\Phi$  constant and measuring  $V_{SPV}$ , is to determine the value of  $\Phi$  necessary to produce a constant  $V_{SPV}$  for each wavelength of light used. The former method is called Method B, and the latter is called Method A. Since the variation in  $V_{SPV}$  is not linear with  $\Phi$ , Method A is preferred, and Method A was specified in Goodman's original paper.

Goodman made the following assumptions to arrive at the simplified equation for  $V_{SPV}$  used to compute diffusion length.

1. The thickness of the sample is much greater than the penetration of the light
2. The depth of the depletion region is much less than the penetration of the light
3. The thickness of the sample is much greater than the diffusion length
4. The depth of the depletion region is much less than the diffusion length
5. The excess carriers created by the light are negligible compared to the concentration of majority carriers.

Under these assumptions, the following holds true.

$$\frac{\Phi}{V_{SPV}} = f \left[ C * \left( L + \frac{1}{\alpha} \right) \right]$$

where  $f$  is a function dependent on the type of semiconductor, the doping, and the surface treatment  
 $C$  is a constant, incorporating many other things that are assumed to be constant  
 $L$  is the diffusion length  
 $\alpha$  is the absorption coefficient of the light wavelength (and  $1/\alpha$  is the penetration depth)

A plot of  $\Phi/V_{SPV}$  will intersect the X-axis at  $-L$ , minus the diffusion length. Thus, measurement of diffusion length “falls out of the equations.”

The measurement can be made using two or more wavelengths of light. Using additional wavelengths, and determining the best-fit straight line, can result in a measurement that is more accurate, assuming all of the assumptions are still satisfied.