Depletion-Layer Photoeffects in Semiconductors

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The theory of photoconduction through the reverse-biased p-n junction in semiconductors is developed without the customary assumption that carrier generation in the junction depletion layer is negligible. Different from previous theories, the more general treatment leads to a voltage dependence of the photocurrent and its spectral distribution. When the incident light beam is modulated at frequencies comparable to the transit time through the depletion layer, a phase shift between the photon flux and photocurrent is noticed and transit-time rectification occurs.

1. INTRODUCTION[1]

IT has been customary in theories of the photoeffect across semiconductor p-n junctions to neglect generation of carriers inside the junction depletion layer.[2] This, however, does not seem justified for the surface barrier or surface junction photoeffect[3–10] (see Fig. 1) where the junction is illuminated through a very thin transparent metal or semiconductor contact. The direction of incident illumination is perpendicular to the plane of the barrier or junction. Depending on the wavelength of the incident light and the semiconductor used, a certain percentage or all the incident light is absorbed in the depletion layer of the barrier. This can be easily verified by considering, e.g., the optical absorption coefficients of germanium and silicon. The photocurrent through the barrier will, therefore, consist of two contributions; one due to the carriers generated inside the depletion layer, and another due to carriers generated in the adjacent bulk material and diffusing into the junction. Since the thickness of the depletion layer, and thus the number of generated carriers which actually cross the junction, varies as a function of the voltage across the junction, deviations from the usual theory of the p-n junction photoeffect are observed, in particular, in the reverse biased condition.

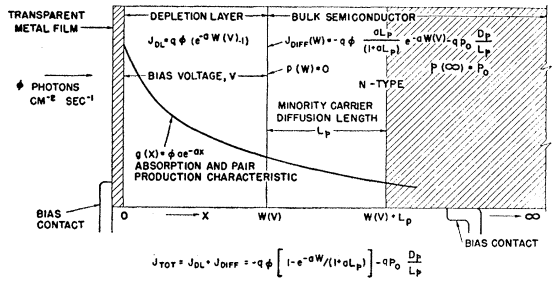
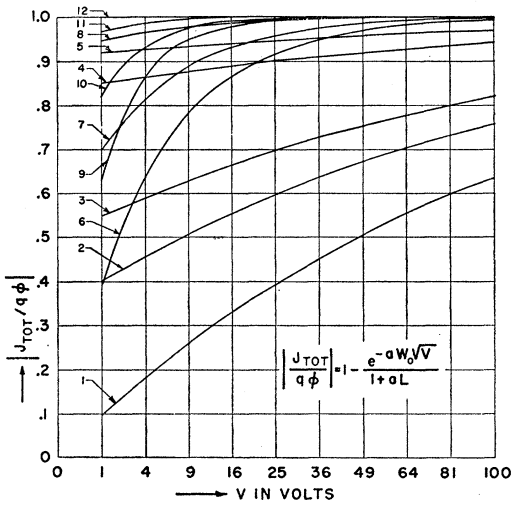


FIG. 1. On the derivation of the depletion layer photoeffect.

2. THEORY OF THE DEPLETION LAYER PHOTOEFFECT UNDER STEADY-STATE CONDITIONS

The total photocurrent density under monochromatic illumination and reverse bias has been derived in Appendix A and is given by

$$J_{TOT} = -q\Phi[1-e^{-aW}/(1+aL_p)] - qp_0D_p/L_p. \quad (1)$$



CURVE NO.	aW_0	aL
1	.1	0
2	.1	.5
3	.1	1
4	.1	5
5	.1	10
6	.5	0
7	.5	1
8	.5	10
9	1	0
10	1	1
11	1	10
12	10	0

FIG. 2. Normalized photocurrent *vs* bias voltage for constant light intensity, homogeneous impurity distribution, and various relative values of absorption coefficient, a, minority carrier diffusion length, L, and width constant, W_0, of the depletion layer.

[1] A preliminary account of this work has been given in a paper by W. W. Gärtner and H. Mette, Bull. Am. Phys. Soc. 3, 219 (1958).
[2] For an exception see H. Y. Fan, Bull. Am. Phys. Soc. 24, 14 (1949).
[3] S. Benzer, J. Appl. Phys. 20, 804 (1949).
[4] J. I. Pantchechnikoff, Rev. Sci. Instr. 23, 135 (1952).
[5] E. Simon, Purdue University Report, July 1, 1953 (unpublished).
[6] Gossick, Mayer, and Kemmerly, Purdue University Report, November, 1955 (unpublished).
[7] E. Simon, Transitron Electronic Corporation Report, May 1, 1956 (unpublished).
[8] H. Mette and W. W. Gärtner, Bull. Am. Phys. Soc. 3, 219 (1958).
[9] W. W. Gärtner, Proc. Inst. Radio Engrs. 46, 1422 (1958).
[10] Ahlstrom, Mette, Loscoe, and Gärtner, Institute for Radio Engineers—Professional Group for Electron Devices, Electron Devices Meeting, Washington, D. C., October 30, 1958 (unpublished).

The meanings of the symbols are explained in Appendix A. The depletion layer thickness, W, is a function of the voltage and impurity distribution across the junction. For homogeneous impurity density, one obtains

$$W=W_0\sqrt{V}, \tag{2}$$

where W_0 is the "width constant" of the depletion layer (equal to its width at a voltage of 1 volt), and V is the voltage across it. Figure 2 shows in normalized form how the photocurrent for a given light intensity varies with bias voltage. The curve parameters are the diffusion length, L, the absorption coefficient, a, and the width constant, W_0. One notices that, depending on the wavelength of the incident radiation, the impurity content, and the lifetime in the semiconductor, the photocurrent may vary with applied voltage by more than a factor of 6. The effect which does not exist in previous theories is most pronounced for short lifetimes and deep optical penetration.

Figure 3 shows how the photocurrent depends on diffusion length. Such curves could, e.g., be measured by varying the temperature of the photocell (thus changing lifetime and diffusion constant). One observes that the dependence is different for different bias voltages, which is not obtained with previous theories.

Figure 4 illustrates the voltage dependence of the spectral distribution of the depletion layer photoeffect with the diffusion length, L, and width constant, W_0, as the additional parameters. One notices that there may be as much as a factor of three difference in the response to a given wavelength, depending on the amount of reverse bias on the junction.

The effects mentioned so far all occur under steady-state conditions. It is, however, also of interest to investigate the behavior of the depletion-layer photoeffect under rapid transient conditions, the simplest case of which is discussed in the following.

3. TRANSIT TIME EFFECTS AT HIGH MODULATION FREQUENCIES

Since the carriers require a finite time to traverse the depletion layer, a phase difference between the

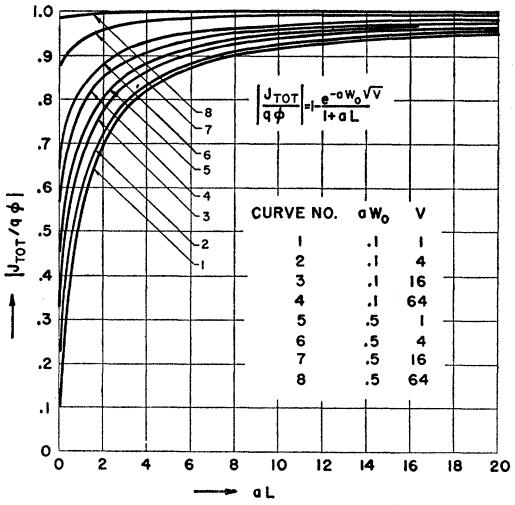


FIG. 3. Normalized photocurrent *vs* normalized diffusion-length for minority carriers, aL, for constant light intensity, homogeneous impurity distribution and various relative values of absorption coefficient, a, width constant, W_0, and bias voltage, V.

photon flux and the photovoltage and current will appear when the incident light intensity is modulated rapidly. To obtain a quantitative feeling for this phenomenon, we consider the simplest case of a *p-i-n* depletion layer as shown in Fig. 5(a). It consists of a layer of near-intrinsic semiconductor sandwiched between two highly doped or even metallic regions. The applied voltage is assumed to be high enough to deplete the intrinsic region and to insure constant field-independent carrier velocity, u. If we further assume all series resistances and capacitances to be negligible, the derivation carried out in Appendix B shows that the short-circuit current density is given by

$$j_{sc}=q\Phi[(1-e^{j\omega t_0})/(j\omega t_0)]. \tag{3}$$

The attenuation factor in the square brackets is plotted in Fig. 5(b). One notices that the amplitude of the ac photocurrent decreases rapidly with frequency when ωt_0 exceeds unity. The response time of the depletion

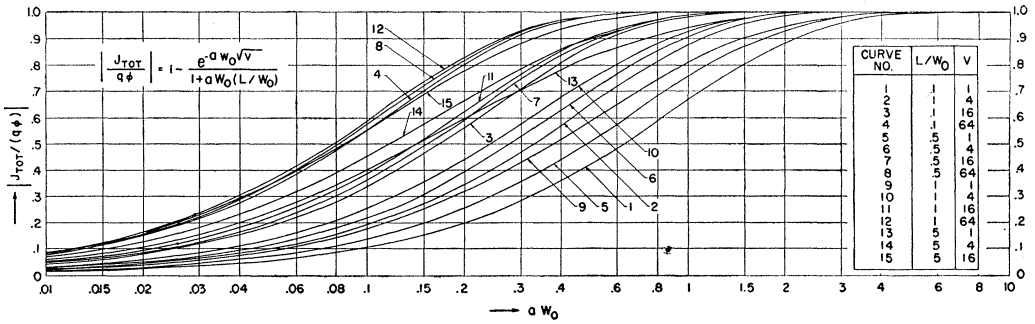


FIG. 4. Spectral distribution of the depletion layer photoeffect. Normalized photocurrent has been plotted *vs* normalized absorption coefficient, aW_0, for various values of applied voltage, V, and normalized diffusion length, L/W_0.

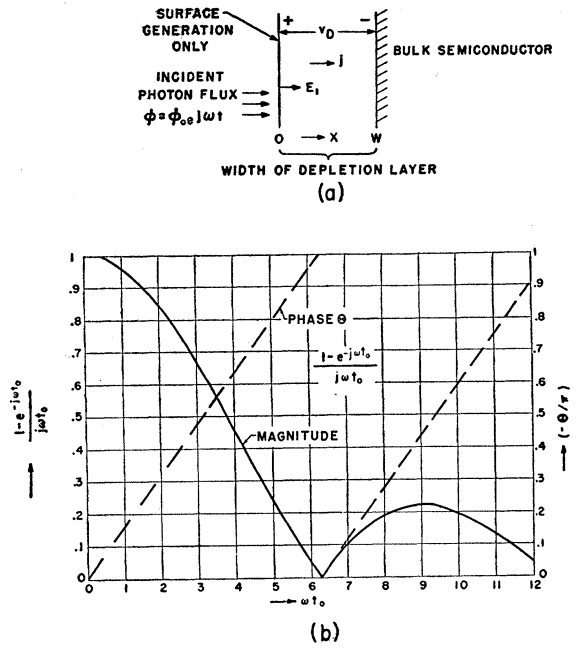


FIG. 5. Analysis of transit time effects in the transport of photocarriers through depletion layers at high frequencies. (a) Geometry assumed for the analysis. (b) Photoresponse (normalized current or voltage) *vs* normalized modulation frequency of incident photon flux.

layer photoeffect is thus limited by the carrier transit time through the depletion layer. For frequencies $\omega > 1/t_0$, phase shift and appreciable transit-time rectification occur. With u of the order of 10^7 cm/sec and W of the order of 10^{-3} cm, one may obtain $t_0 \simeq 10^{-10}$ sec in germanium or silicon.

4. ACKNOWLEDGMENTS

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APPENDIX A. PHOTOCURRENT THROUGH REVERSE-BIASED DEPLETION LAYER

The total current density through the reverse-biased depletion layer is given by

$$J_{\mathrm{TOT}} = J_{\mathrm{DL}} + J_{\mathrm{DIFF}}, \tag{A.1}$$

where J_{DL} is the drift current density due to carriers generated inside the depletion layer, and J_{DIFF} is the diffusion current density of minority carriers generated outside the depletion layer in the bulk of the semiconductor and diffusing into the reverse-biased junction. Recombination and thermal generation of carriers inside the junction will be neglected, but may be noticeable in material with a high concentration of recombination centers, and then would cause additional modifications of the theory. We consider monochromatic radiation only, in which case the absorption and pair production characteristic is given by

$$g(x) = \Phi a e^{-ax}. \tag{A.2}$$

$g(x)$ and other pertinent quantities are shown in Fig. 1. $g(x)$ is the generation rate (density generated per unit time), Φ is the total incident photon flux, ($\Phi = \int_0^\infty g(x)dx$), and a is the monochromatic absorption coefficient. J_{DL} is thus found to be equal to

$$J_{\mathrm{DL}} = q\int_0^W g(x)dx = q\Phi(e^{-aW} - 1). \tag{A.3}$$

For definiteness let us consider an n-type semiconductor. In this case, the hole density in the bulk semiconductor region, $x > W$, is determined from the diffusion equation:

$$D_p p'' - (p - p_0)/\tau + g(x) = 0, \tag{A.4}$$

where D_p is the diffusion coefficient for holes, p is the hole density, p_0 is the equilibrium hole density, and τ is the lifetime of excess carriers. The solution of Eq. (A.4) under the boundary conditions

$$p = p_0 \quad \text{for} \quad x = \infty, \tag{A.5}$$

and

$$p = 0 \quad \text{for} \quad x = W \tag{A.6}$$

is given by

$$p = p_0 - (p_0 + Ae^{-aW})e^{(W-x)/L_p} + Ae^{-ax}, \tag{A.7}$$

with $L_p = (D_p\tau)^{\frac{1}{2}}$ and

$$A = (\Phi/D_p)\frac{a^2L_p^2}{a(1-a^2L_p^2)}. \tag{A.8}$$

The diffusion current density, $J_{\mathrm{DIFF}} = qD_p p'$, at $x = W$ is thus obtained as

$$J_{\mathrm{DIFF}} = -q\Phi\frac{aL_p}{(1+aL_p)}e^{-aW} - qp_0\frac{D_p}{L_p}. \tag{A.9}$$

The total current density through the depletion layer is then given by the sum of Eqs. (A.3) and (A.9), and is shown in Fig. 1.

APPENDIX B. DERIVATION OF CURRENT-VOLTAGE RELATIONSHIP FOR SINUSOIDALLY VARYING INCIDENT LIGHT INTENSITY

We assume (a) surface generation only [see Fig. 5(a)], (b) constant carrier velocity, u, (c) unit quantum efficiency (one electron generated per incident photon), (d) a photon flux density given by $\Phi = \Phi_0 e^{j\omega t}$ photons cm^{-2} sec^{-1}. The conduction current density, j_{COND}, at point x is then found to be

$$j_{\mathrm{COND}}(x) = q\Phi_0 e^{j\omega(t-x/u)}. \tag{B.1}$$

Since $\operatorname{div} j_{TOT}=0$, one may write

$$j_{TOT}=\frac{1}{W}\int_0^W\left(j_{COND}+\epsilon\frac{\partial E}{\partial t}\right)dx, \qquad (B.2)$$

where the second term in the parentheses is the displacement current density. Substituting Eq. (B.1), we find

$$j_{TOT}=j\omega\epsilon v_D/W+q\Phi(1-e^{-j\omega t_0})/(j\omega t_0), \qquad (B.3)$$

where $t_0=W/u$ is the transit time of carriers through the depletion region, and v_D is the voltage across the depletion layer. From Eq. (B.3) the open-circuit voltage ($j_{TOT}=0$) and the short-circuit current ($v_D=0$) may be calculated.

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N^{14}-N^{15} Hyperfine Anomaly*

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The optical transmission of an optically oriented sodium vapor in spin-exchange equilibrium with atomic nitrogen has been used to measure the zero-field hyperfine splitting of N^{14} and N^{15}. The ground state of atomic nitrogen is $^4S_{3/2}$. For N^{14}, which has $I=1$,

$$\Delta\nu_{5/2\to3/2}=26.12721\pm0.00018 \text{ Mc/sec},$$
$$\Delta\nu_{3/2\to1/2}=15.67646\pm0.00012 \text{ Mc/sec}.$$

For N^{15}, which has $I=\frac{1}{2}$,

$$\Delta\nu=29.29136\pm0.00016 \text{ Mc/sec}.$$

The nuclear moments of N^{14} and N^{15} have been remeasured by observing the effect of saturating the nitrogen resonance on the proton resonance in NH_4^+. The results were

$$g(14)/g(H^1)=0.072\,236\,95\pm0.000\,000\,08,$$

and

$$g(15)/g(H^1)=-0.101\,330\,93\pm0.000\,000\,08.$$

The $N^{14}-N^{15}$ hyperfine anomaly obtained by combining these measurements is

$$\Delta=\frac{A(15)/A(14)}{g(15)/g(14)}-1=0.000\,983\pm0.000\,017.$$

A short discussion of the mechanism of spin-exchange collisions is given.

INTRODUCTION

THE atomic ground state of nitrogen is $(1s)^2(2s)^2(2p)^3$, $^4S_{\frac{3}{2}}$. If there were no configuration mixing for this atom, there would be no nuclear hyperfine interaction or nuclear quadrupole interaction.[1,2] This can easily be seen since the total orbital angular momentum is zero so that the wave function is spherically symmetric and in the nonrelativistic approximation a p electron does not contribute to the Fermi contact interaction. Heald and Beringer[3] used the method of paramagnetic resonance absorption in a gas to make measurements on atomic N^{14} and found that the magnetic dipole hyperfine interaction constant was 10.45 ± 0.02 Mc/sec. They could detect no nuclear quadrupole interaction. Their large line width of 250 kc/sec, which was attributed to a combination of magnetic field inhomogeneity, Doppler broadening, and atom-atom interaction, made it difficult to determine the small magnetic dipole hyperfine interaction constant precisely. They showed that the g factor of the atomic ground state was the same as that of the free electron as would be expected for pure L-S coupling.

The discovery[4–7] that the hyperfine transitions of S-state atoms could be detected by using spin-exchange collisions with optically oriented sodium atoms has made it possible to measure the nitrogen hyperfine splitting more precisely. In this measurement the nitrogen resonance is observed by monitoring the transmission of circularly polarized resonance radiation through a bulb

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[1] S. Goudsmit, Phys. Rev. **37**, 663 (1931).

[2] R. E. Trees, Phys. Rev. **92**, 308 (1953).

[3] M. A. Heald and R. Beringer, Phys. Rev. **96**, 645 (1954).

[4] H. G. Dehmelt, Phys. Rev. **109**, 38 (1958).

[5] Franken, Sands, and Hobart, Phys. Rev. Letters **1**, 52, 118(E) (1958).

[6] R. Novick and H. E. Peters, Phys. Rev. Letters **1**, 54 (1958).

[7] Anderson, Pipkin, and Baird, Phys. Rev. Letters **1**, 229 (1958).