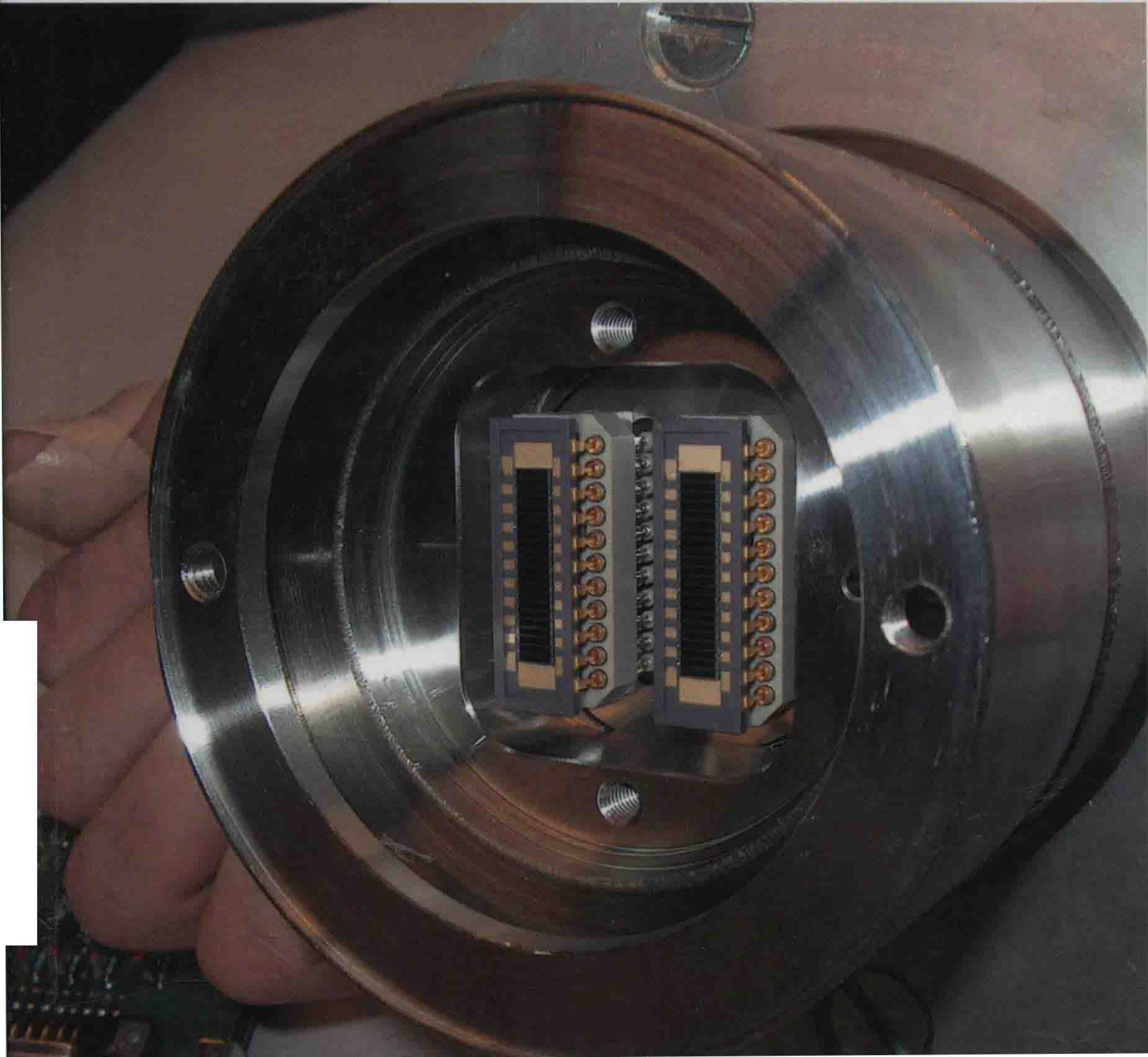
Theory and Applications of Photodiodes

Kate Brown



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Preface

This book has been an outcome of determined endeavour from a group of educationists in the field. The primary objective was to involve a broad spectrum of professionals from diverse cultural background involved in the field for developing new researches. The book not only targets students but also scholars pursuing higher research for further enhancement of the theoretical and practical applications of the subject.

A photodiode is described as a semiconductor diode which generates a potential difference or changes its electrical resistance when it is exposed to light. This book reflects current development and expansion of photodiodes, inclusive of the primary reviews and the precise applications developed by the writers themselves. The key thought behind this book is to enable authors to deal with a broad variety of background and highlight the progresses in photodiode-related areas. This book discusses new problems and connected solutions in various areas of primary physics; design and tool and circuit applications. We intend to help students, and even experts, in understanding the concept in a simpler way. This book will be a good source of reference to anyone who holds interest in optoelectronic devices.

It was an honour to edit such a profound book and also a challenging task to compile and examine all the relevant data for accuracy and originality. I wish to acknowledge the efforts of the contributors for submitting such brilliant and diverse chapters in the field and for endlessly working for the completion of the book. Last, but not the least; I thank my family for being a constant source of support in all my research endeavours.

Editor

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Viacheslav Kholodnov and Mikhail Nikitin

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1. Introduction

Minimal value of dark current in reverse biased $p-n$ junctions at avalanche breakdown is determined by interband tunneling. For example, tunnel component of dark current becomes dominant in reverse biased $p-n$ junctions formed in a number semiconductor materials with relatively wide gap E_g already at room temperature when bias V_b is close to avalanche breakdown voltage V_{BD} (Sze, 1981), (Tsang, 1981). The above statement is applicable, for example, to $p-n$ junctions formed in semiconductor structures based on ternary alloy $In_{0.53}Ga_{0.47}As$ which is one of the most important material for optical communication technology in wavelength range λ up to 1.7 μm (Tsang, 1981), (Stillman, 1981), (Filachev et al, 2010), (Kim et al, 1981), (Forrest et al, 1983), (Tarof et al, 1990), (Ito et al, 1981). Significant decreasing of tunnel current can be achieved in avalanche photodiode (APD) formed on multilayer heterostructure (Fig. 1) with built-in $p-n$ junction when metallurgical boundary of $p-n$ junction ($x=0$) lies in wide-gap layer of heterostructure (Tsang, 1981), (Stillman, 1981), (Filachev et al, 2010), (Kim et al, 1981), (Forrest et al, 1983), (Tarof et al, 1990), (Clark et al, 2007), (Hayat & Ramirez, 2012), (Filachev et al, 2011). Design and specification of heterostructure for creation high performance APD must be such that in operation mode the following two conditions are satisfied. First, space charge region (SCR) penetrates into narrow-gap light absorbing layer (absorber) and second, due to decrease of electric field $E(x)$ into depth from $x=0$ (Fig. 1), process of avalanche multiplication of charge carriers could only develop in wide-gap layer. This concept is known as APD with separate absorption and multiplication regions (SAM-

APD). Suppression of tunnel current is caused by the fact that higher value of E corresponds to wider gap E_g. Electric field in narrow-gap layer is not high enough to produce high tunnel current in this layer. Dark current component due to thermal generation of charge carriers in SCR (thermal generation current with density J_G) is proportional to intrinsic concentration of charge carriers $n_i \propto \exp(-E_g / 2k_B T)$, here k_B – Boltzmann constant, T – temperature (Sze, 1981), (Stillman, 1981). Tunnel current density J_T grows considerably stronger with narrowing E_g than n_i and depends weakly on T (Stillman, 1981), (Burstein & Lundqvist, 1969). Therefore, component J_T will prevail over J_G in semiconductor structures with reasonably narrow gap E_g even at room temperature. Another dark current component – diffusion-drift current caused by inflow of minority charge carriers into SCR from quasi-neutral regions of heterostructure is proportional to $n_i^2 \times N^{-1}$ (Sze, 1981), (Stillman, 1981) (where N is dopant concentration). To eliminate it one side of $p-n$ junction is doped heavily and narrow-gap layer is grown on wide-gap isotype heavily doped substrate (Tsang, 1981). Thus heterostructure like as $p_{wg}^{+} - n_{wg} - n_{ng} - n_{wg}^{+}$ is the most optimal, where subscript ‹wg› means wide-gap and ‹ng› – narrow-gap, properly. To ensure tunnel current's density not exceeding preset value is important to know exactly allowable variation intervals of dopants concentrations and thicknesses of heterostructure's layers. Thickness of narrow-gap layer W_2 is defined mainly by light absorption coefficient γ and speed-of-response. But as it will be shown further tunnel current's density depends strongly on thickness of wide-gap layer W_1 and dopant concentrations in wide-gap N_1 and narrow-gap N_2 layers. Approach to optimize SAM-APD structure was proposed in articles (Kim et al, 1981), (Forrest et al, 1983) (see also (Tsang, 1981)). Authors have developed diagram for physical design of SAM-APD based on heterostructure including $In_{0.53}Ga_{0.47}As$ layer. However, diagram is not enough informative, even incorrect significantly, and cannot be reliably used for determining allowable variation intervals of heterostructure's parameters. The matter is that diagram was developed under assumption that when electric field $E(x)$ (see Fig. 1b) at metallurgical boundary of $p_{wg}^{+} - n_{wg}$ junction $E(0) \equiv E_1$ is higher than 4.5×10^5 V/cm then avalanche multiplication of charge carriers occurs in InP layer where $p_{wg}^{+} - n_{wg}$ junction lies at any dopants concentrations and thicknesses of heterostructure's layers. However, electric field $E_1 = E_{1BD}$ at which avalanche breakdown of $p-n$ junction occurs depends on both doping and thicknesses of layers (Sze, 1981), (Tsang, 1981), (Osipov & Kholodnov, 1987), (Kholodnov, 1988), (Kholodnov, 1996-2), (Kholodnov, 1996-3), (Kholodnov, 1998), (Kholodnov & Kurochkin, 1998). As a consequence, avalanche multiplication of charge carriers in considered heterostructure can either does not occur at electric field value E_1=4.5×10^5 V/cm or occurs in narrow-gap layer (Osipov & Kholodnov, 1987), (Osipov &, Kholodnov, 1989). Value of electric field required to initialize avalanche multiplication of charge carriers can even exceed E_{1BD} (Sze, 1981), (Osipov & Kholodnov, 1987), (Kholodnov, 1996-2), (Kholodnov, 1996-3), (Kholodnov, 1998), (Kholodnov & Kurochkin, 1998) that has physical meaning in the case of transient process only (Groves et al, 2005), (Kholodnov, 2009). Further, in development of diagram was assumed that maximal allowable value of electric field in absorber at hetero-interface with multiplication layer E_2 (see Fig. 1b) is equal to 1.5×10^5 V/cm. But tunnel current density J_T in narrow-gap absorber $In_{0.53}Ga_{0.47}As$ (Osipov & Kholodnov, 1989) is much smaller at that value of electric field than density of thermal generation current J_G which in the best samples of $InP-In_{0.53}Ga_{0.47}As-InP$ heterostructures (Tsang, 1981), (Tarof et al, 1990), (Braer et al, 1990) can be up to 10^{-6} A/cm^2. However, diagram does not take into account the fact that tunnel current in wide-gap multiplication layer can be much greater than in narrow-gap absorber (Osipov & Kholodnov, 1989). Therefore, total tunnel current can exceed thermal generation current.

In present chapter is done systematic analysis of interband tunnel current in avalanche heterophotodiode (AHPD) and its dependence on dopants concentrations N_1 in n_{wg}wide-gap and N_2 in n_{ng}narrow-gap layers of heterostructure and thicknesses W_1 and W_2, respectively (Fig. 1) and fundamental parameters of semiconductor materials also. Performance limits of AHPDs are analyzed (Kholodnov, 1996). Formula for quantum efficiency η of heterostructure is derived taking into account multiple internal reflections from hetero-interfaces. Concentration-thickness nomograms were developed to determine allowable variation intervals of dopants concentrations and thicknesses of heterostructure layers in order to match preset noise density and avalanche multiplication gain of photocurrent. It was found that maximal possible AHPD's speed-of-response depends on photocurrent's gain due to avalanche multiplication, as it is well known and permissible noise density for preset value of photocurrent's gain also. Detailed calculations for heterostructure $InP-In_{0.53}Ga_{0.47}As-InP$ are performed. The following values of fundamental parameters of InP (I, Fig. 1) and $In_{0.53}Ga_{0.47}As$ (II, Fig. 1) materials (Tsang, 1981), (Stillman, 1981), (Kim et al, 1981), (Forrest et al, 1983), (Tarof et al, 1990), (Ito et al, 1981), (Braer et al, 1990), (Stillman et al, 1983), (Burkhard et al, 1982), (Casey & Panish, 1978) are used in calculations: band-gaps E_{g1}= 1.35 eV and E_{g2}= 0.73 eV; intrinsic charge carriers concentrations $n_i^{(1)}=10^8$ cm^{-3} and $n_i^{(2)}=5.4\times10^{11}$ cm^{-3}; relative dielectric constants ε_1 = 12.4 and ε_2=13.9; light absorption coefficient in $In_{0.53}Ga_{0.47}As$ $\gamma=10^4$ cm^{-1}; specific effective masses $m^* = 2m_c \times m_v/(m_c + m_v)$ of light carriers m_1= $0.06m_0$ and m_2= $0.045m_0$, where m_0 – free electron mass. The chapter material is presented in analytical form. For this purpose simple formulas for avalanche breakdown electric field E_{BD} and voltage V_{BD} of $p-n$ junction are derived taking into account finite thickness of layer. Analytical expression for exponent in well-known Miller's relation was obtained (Sze, 1981), (Tsang, 1981), (Miller, 1955) which describes dependence of charge carriers' avalanche multiplication factors on applied bias voltage V_b. It is shown in final section that Geiger mode (Groves et al, 2005) of APD operation can be described by elementary functions (Kholodnov, 2009).

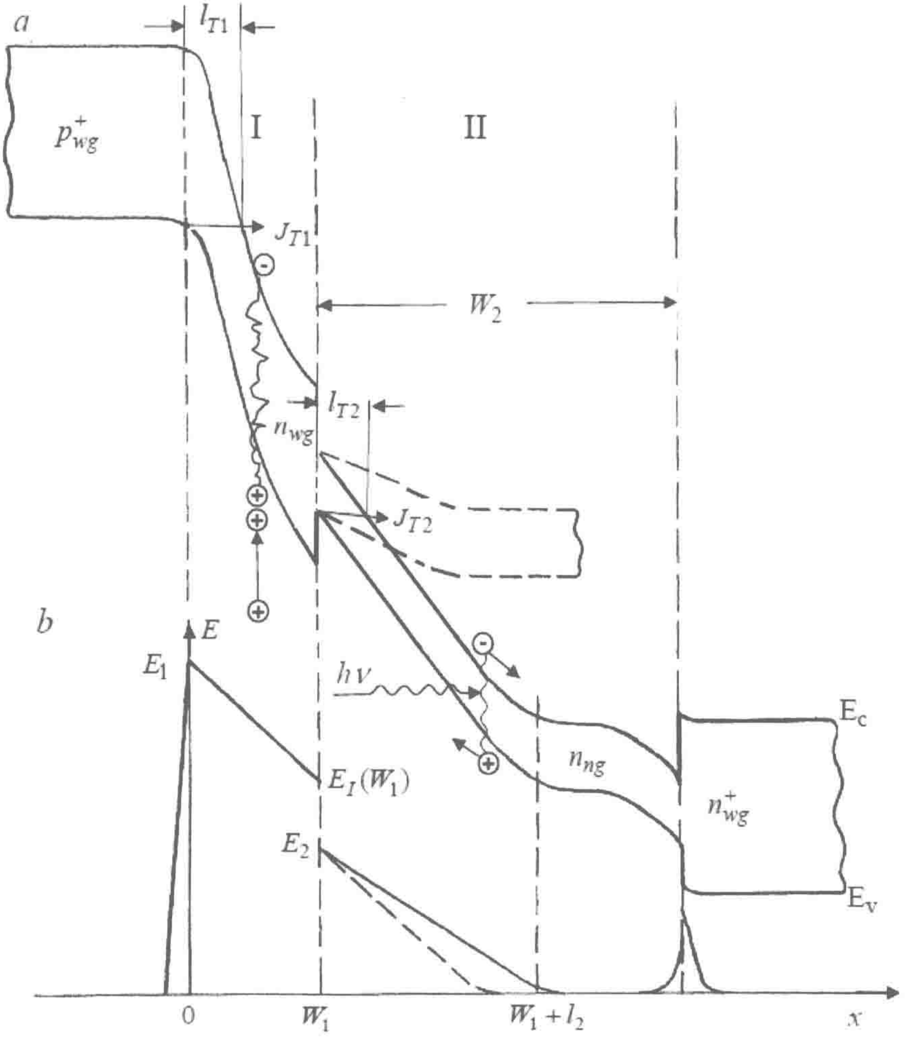

Figure 1. Energy diagram of heterostructure in operation mode (**a**) and electric field distribution in it (**b**). E_c and E_v – energy of conduction band bottom and valence band top. Solid lines – $N_2 = N_2^{(1)}$, dashed – $N_2 > N_2^{(1)}$

2. Formulation of the problem: Basic relations

Let's consider $p^+_{wg} - n_{wg} - n_{ng} - n^+_{wg}$ heterostructure at reverse bias V_b sufficient to initialize avalanche multiplication of charge carries. This structure is basic for fabrication of AHPDs.

From relations (Sze, 1981), (Tsang, 1981), (Filachev et al, 2011), (Grekhov & Serezhkin, 1980), (Artsis & Kholodnov, 1984)

$$M_n = M(-L_p), M_p = M(L_n), \tilde{M}(-L_p, L_n) = \int_{-L_p}^{L_n} g(x)M(x)dx \Bigg/ \int_{-L_p}^{L_n} g(x)dx, \tag{1}$$

$$M(x) = Y(x,-L_p)/(1-m), m(-L_p, L_n) = \int_{-L_p}^{L_n} \alpha(x)Y(x,-W_p)dx, Y(x,x_0) = \exp\left[\int_{x_0}^{x} (\beta-\alpha)dx'\right] \tag{2}$$

can be determined, in principal, dependences of multiplication factors M in $p-n$ structures on V_b, where M_n and M_p – multiplication factors of electrons and holes inflow into space charge region (SCR); value of multiplication factor of charge carriers generated in SCR $\widetilde{M}$ lies between M_n and M_p; specific rate of charge carriers' generation in SCR $g = g_d + g_{ph}$ consists of dark g_d and photogenerated g_{ph} components; L_p and L_n – thicknesses of SCR in p and n sides of structure; $\alpha(E)$ and $\beta(E) = K(E) \times \alpha(E)$ – impact ionization coefficients of electrons $\alpha(E)$ and holes $\beta(E)$; $E(x)$ – electric field. Let's denote by N_{1pt} dopant concentration N_1 so that for $N_1 < N_{1pt}$ "punch-through" (depletion) of n_{wg} layer occurs that means penetration of non-equilibrium SCR into n_{ng} layer (Fig. 1). Optical radiation passing through wide-gap window is absorbed in n_{ng} layer and generates electron-holes pairs in it. When $N_1 < N_{1pt}$ then photo-holes appearing near n_{wg}/n_{ng} heterojunction ($x = W_1$) are heated in electric field of non-equilibrium SCR and, at moderate discontinuities in valence band top E_v at $x = W_1$, photo-holes penetrate into n_{wg} layer (layer I) due to emission and tunneling. If W_1 is larger than some value $W_{1\min}(N_1, N_2, W_2)$ (Osipov & Kholodnov, 1989), which is calculated below, then avalanche multiplication of charge carriers occurs only in n_{wg} layer, i.e. photo-holes fly through whole region of multiplication. In this case photocurrent's gain (Tsang, 1981), (Artsis & Kholodnov, 1984) $M_{ph} = M_p$. Let p_{wg}^{+} layer is doped so heavy that avalanche multiplication of charge carriers in it can be neglected (Kholodnov, 1996-2), (Kholodnov & Kurochkin, 1998). Under these conditions thicknesses in relations (1) and (2) can be put $L_p = 0$ and $L_n = W_1$, i.e.

$$M_{ph} = Y(W_1, 0)/[1 - m(0, W_1)] \tag{3}$$

It is remarkable that responsivity $S_I(\lambda)$ (where λ – is wavelength) of heterostructure increases dramatically once SCR reaches absorber n_{ng} (layer II on Fig. 1) and then depends weakly on bias V_b till avalanche breakdown voltage value V_{BD} (Stillman, 1981). This effect is caused by potential barrier for photo-holes on n_{wg}/n_{ng} heterojunction and heating of photo-holes in electric field of non-equilibrium SCR. If losses due to recombination are negligible (Sze, 1981), (Tsang, 1981), (Stillman, 1981), (Forrest et al, 1983), (Stillman et al, 1983), (Ando et al, 1980), (Trommer, 1984), for example, at punch-through of absorber, then $S_I(\lambda)$ in operation mode is determined by well-known expression (Sze, 1981), (Tsang, 1981), (Stillman, 1981), (Filachev et al, 2011):

$$S_I(\lambda) = \eta(\lambda) \times \frac{\lambda}{1.24} \times M_{ph} \tag{4}$$

where λ in μm and value of quantum efficiency η is considered below. Photocurrent gaining and large drift velocity of charge carriers in SCR allow creating high-speed high-performance photo-receivers with APDs as sensitive elements (Sze, 1981), (Tsang, 1981), (Filachev et al, 2010), (Filachev et al, 2011), (Woul, 1980). Reason is high noise density of external electronics circuit at high frequencies or large leakage currents that results in decrease in Noise Equivalent Power (NEP) of photo-receiver with increase of M_{ph} despite of growth APD's noise-to-signal ratio (Tsang, 1981), (Filachev et al, 2011), (Woul, 1980), (McIntyre, 1966). Decrease in NEP takes place until M_{ph} becomes higher then certain value M_{ph}^{opt} above which noise of APD becomes dominant in photo-receiver (Sze, 1981), (Tsang, 1981), (Filachev et al, 2011), (Woul, 1980). Even at low leakage current and low noise density of external electronics circuit, avalanche multiplication of charge carriers may lead to degradation in NEP of photo-receiver due to decreasing tendency of signal-to-noise ratio dependence on APD's M_{ph} under certain conditions (Artsis & Kholodnov, 1984). Moreover, excess factor of avalanche noise (Tsang, 1981), (Filachev et al, 2011), (Woul, 1980), (McIntyre, 1966) may decrease with powering of avalanche process as, for example, in metal-dielectric-semiconductor avalanche structures, due to screening of electric field by free charge carriers (Kurochkin & Kholodnov 1999), (Kurochkin & Kholodnov 1999-2). Using results obtained in (Artsis & Kholodnov, 1984), (McIntyre, 1966), noise spectral density S_N of $p_{wg}^{+} - n_{wg} - n_{ng} - n_{wg}^{+}$ heterostructure which performance is limited by tunnel current can be written as:

$$S_N = 2 \times q \times A_S \times M_{ph}^2 \times \sum_{i=1}^{2} J_{T,i}(V) F_{ef,i}(M_{ph}), \tag{5}$$

where q – electron charge; A_S – cross-section area of APD's structure; $F_{ef,i}(M_{ph})$ – effective noise factors (Artsis & Kholodnov, 1984) in wide-gap multiplication layer ($i=1$) and in absorber ($i=2$); $J_{T,i}(V)$ – densities of primary tunnel currents in those layers, i.e. tunnel currents which would exist in layers I and II in absence of multiplication of charge carriers due to avalanche impact generation. Comparison of two different APDs in order to determine which one is of better performance is reasonable only at same value of M_{ph}. Expression (5) shows, that for preset gain of photocurrent, noise density is determined by values of pri-