Modeling on Current-Voltage Characteristics of HgCdTe Photodiodes in Forward Bias Region

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***Abstract*— Current-voltage (*I–V*) characteristics of HgCdTe photodiodes in the forward bias region have been modeled on account of mechanisms including diffusion and recombination currents, metal-semiconductor (*M-S*) contact and constant series resistance. Moreover, a data processing approach has been developed to obtain valuable physical parameters from measured *I–V* curves. This model and algorithm have also been verified to be available and promising by the fitting results on device parameters of HgCdTe photodiodes.**

I. INTRODUCTION

Mercury cadmium telluride (HgCdTe) is the most widely used material system for infrared (IR) imaging applications [1–4]. Unfortunately, detectors based on this material suffer from very complex fabrication processes. Therefore, feasible models are required to simulate the device performance and acquire useful physical parameters. Many researches have been carried out on modeling the current-voltage (*I–V*) characteristics of HgCdTe photodiodes. However, most of them focused only on reverse bias or small bias region [2–3], and the information embedded in forward bias region have been dissipated.

In this work, forward-biased *I–V* characteristics of HgCdTe photodiodes have been modeled, considering diffusion current, recombination current, and the effects of metal-semiconductor (*M-S*) contact as well as a constant series resistance. Several device parameters were obtained from the measured resistance-voltage (*R–V*) data by a set of estimation and fitting techniques. The new method is applicable in evaluating detector quality, and the electrical properties of an *M-S* contact can be extracted directly from photodiodes instead of specially made samples.

II. METHOD

A. Physical Model

The "forward bias" here is a flexible concept, meaning the region where the current grows rapidly with increasing bias and the dynamical impedance accordingly decays to a low value. The diffusion current is given by the following formula:

$$I_{diff} = Aqn_i^2\sqrt{\frac{kT}{q}}\left(\frac{\coth\left(W_p/L_n\right)}{N_a}\sqrt{\frac{\mu_n}{\tau_n}}+\frac{\coth\left(W_n/L_p\right)}{N_d}\sqrt{\frac{\mu_p}{\tau_p}}\right)\left[\exp\left(\frac{qV_1}{kT}\right)-1\right], \quad (1)$$

where V_1 is the effective bias applied on the *p-n* junction, L_n and L_p are the diffusion lengths of electrons and holes; W_p and W_n are the effective thicknesses of *p*- and *n*-region, respectively. The recombination current can be described as such a form that

$$I_{gr} = 2A\frac{n_i kT}{\tau_0}\sqrt{\frac{2\varepsilon_s\varepsilon_0\left(N_a+N_d\right)}{qN_aN_d\left(V_{bi}-V_1\right)}}\sinh\left(\frac{qV_1}{2kT}\right)\cdot f(b), \quad (2)$$

and the meanings of all unexplained symbols in (1) and (2) can be found in [2]. Providing that Schottky barriers only form on *p*-type HgCdTe, *I–V* characteristics of the electrode contact can be expressed as

$$-I = SA^*T^2\exp\left(\frac{-q\phi_{bp}}{kT}\right)\left[\exp\left(\frac{-qV_2}{nkT}\right)-\exp\left(\frac{qV_2}{n_2kT}\right)\right], \quad (3)$$

where $1/n + 1/n_2 = 1$ and V_2 represents the actual voltage drop across the Schottky junction. All symbols' meanings in (3) can be identified by comparing (3) to equations in [4]. In addition, a constant series resistance R_s is incorporated, and the relations $I = I_{diff} + I_{gr}$ and $V = V_1 + V_2 + IR_s$ complete the entire model, in which I and V are the total current and total bias, respectively. This system of equations is to be solved by a two-fold Newton-Raphson method to calculate theoretical *I–V* or *R–V* curves.

A simplified alternative model is presented as follows to enable a preliminary estimation of contact parameters. In the high resistance region, the *p-n* junction bears most external bias and its behavior can be approximated as $I = I_1\exp(qV_1/n_1kT)$, where the saturation current I_1 and the ideality factor n_1 can be determined by the ln*I*–*V* plot. On the other hand, it is necessary to consider the bias divided by the contact in the low resistance region, and invoking $I = I_2\exp(qV_2/n_2kT)$ will easily lead to

$$V = IR_s + \frac{kT\left(n_1+n_2\right)}{q}\ln I - \frac{kT\left(n_1\ln I_1 + n_2\ln I_2\right)}{q}, \quad (4)$$

$$R = \frac{kT\left(n_1+n_2\right)}{q}\frac{1}{I} + R_s, \quad (5)$$

where I_2 can be recognized from (3). With I_1 and n_1 known, least-square analyses would give n_2 and R_s according (5), and thereafter give I_2 (also ϕ_{bp}) according to (4).

B. Fitting Algorithm

Total square relative error in *R–V* data acts as the objective function to be minimized. The fitting algorithm adopted here is a hybrid of the genetic algorithm and a "stirring-like" technique. At first, previously estimated contact parameters remain fixed while other fitting parameters change in a reasonable range in search of the minimum using a real-valued genetic algorithm. Then similar processes will be successively repeated, each time with a random portion of the fitting parameters allowed to vary, until the ultimate terminating condition has been reached. To be specific, the genetic algorithm is implemented via a variant tournament selection, in which the entire population is broken into small groups and several fittest individuals in each group survive to breed. Weighted arithmetic or geometric means of the parents are calculated to carry out crossover, and a gradient

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descent search technique fulfills mutation for those highest-ranking individuals to enhance local searching ability.

III. Application and Disccusion

The photodiodes investigated were planar short-wavelength (SW) photovoltaic detectors fabricated by B^+ implantation on vacancy-doped *p*-type $Hg_{1-x}Cd_xTe$ (x = 0.398) layers grown liquid phase epitaxy (LPE). *I–V* characteristics were measured with zero field of view at 77K, and the fitting parameters were donor density (N_d), effective lifetime in the depletion region (τ_0), electron lifetime in the *p*-region (τ_n), and all three above-mentioned contact parameters, ϕ_{bp}, n and R_s. Nonadjustable parameters were assumed or measured as listed in Table I.

The measured *R–V* data and corresponding fitting results are shown in Fig. 1. A fairly good agreement can be observed between the calculated curve and the experimental one. As the bias increases, the total dynamical impedance is sequentially governed by the effects of recombination, diffusion and *M-S* contact. These results, especially the part magnified in the inset, could not be acquired using only a constant series resistance. Moreover, a well-fitted *I–V* curve was simultaneously achieved and is shown in Fig. 2. As we can see, the original current data would approach a stable negative value of -4.4×10^{-11}A under a small bias, which can be considered as the photocurrent caused by inevitable radiation. After correcting for this point, a more approximate curve to the predicted one was obtained.

In Table II list the extracted values of the fitting parameters, which are all in accordance with those typically reported for similar devices. The value of electron lifetime τ_n corresponds to a diffusion length larger than the *p*-region thickness, which indicates the necessity of using equation of such a form as (1).

TABLE I. Nonadjustalbe Modeling Parameters

Parameter	Value	Parameter	Value	Parameter	Value
N_a (cm^{-3})	5.0×10^{15}	τ_n/τ_p (a.u.)	10.0	E_t/E_g (a.u.)	0.537
W_p (μm)	10.0	μ_p (m^{2}V^{-1}s^{-1})	0.04	A (μm^2)	896
W_n (μm)	1.0	μ_n (m^{2}V^{-3}s^{-3})	5.0	S (mm^2)	7.69

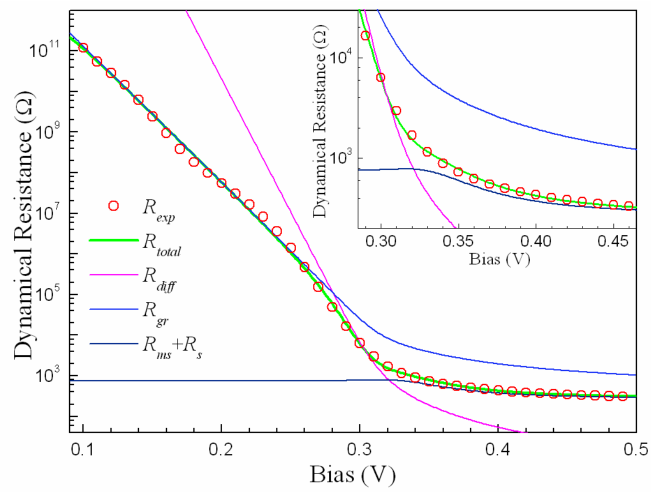

Figure 1. Experimental *R–V* curve and corresponding fitting results.

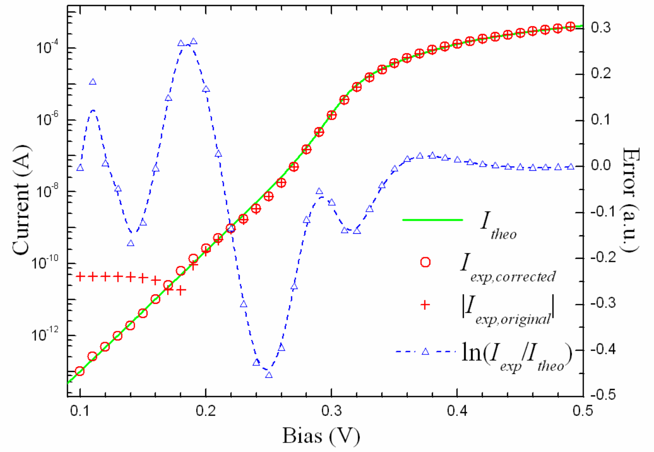

Figure 2. Experimetal and predicted *I–V* curves, as well as corresponding relative errors. Both original and corrected data are depicted.

TABLE II. Values of Extracted Parameters

N_d (cm^{-3})	τ_n (ns)	τ_0 (ns)	ϕ_{bp} (V)	n (a.u.)	R_s (Ω)
6.46×10^{17}	24.0	0.461	0.144	1.75	254

The relatively large ideality factor n implies a notable deviation from pure thermionic emission theory, possibly resulting from tunneling, recombination and so on, which is beneficial to the formation of a low-resistance electrode contact.

IV. Conclusion

I–V characteristics of HgCdTe photodiodes in forward bias region have been successfully modeled, considering the effects of diffusion current, recombination current and especially the rectifying electrode contact. Several physical parameters, such as the donor concentration, the minority carrier lifetime, and the Schottky barrier height of electrode contact, were extracted from the experimental data of a typical SW planar device. Therefore, this novel model and method have been proven applicable in analyzing the properties and quality of HgCdTe photodiodes.

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