SPACE CHARGE ANALYSIS OF Si $n^+ - i$ STRUCTURES WITH APPLICATION TO FAR-INFRARED DETECTORS

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Abstract—The operation mechanism of the Si homojunction interfacial workfunction internal photoemission far-infrared detector is based on internal photoemission occurring at the interfacial barrier between a heavily doped absorber/emitter layer and an intrinsic ($i$) layer. Due to the free carrier "spill over" from the emitter to the $i$ layer, a space charge region is created near the interface, which was neglected in the previous detector performance analyses. In this paper, we calculate the distributions of free electron concentration, ionized donor concentration, potential barrier, and electric field in the space charge region, for an $n^+ - i$ structure with a thick $i$ layer at low temperatures, by numerically solving the drift-diffusion equation. The dependence of these distributions on applied bias, temperature, and $i$ layer doping level, are investigated. By using these results, the previous experimental results obtained from commercial Si $p-i-n$ diodes can be well explained. PACS numbers: 85.60.Gz, 79.60.Jv, 73.40.Lq, 77.50.

NOTATION

- $D_e$: diffusion coefficient for electrons
- $E_i$: Fermi energy in the bulk of the $i$ layer at equilibrium, relative to the conduction band edge
- $E_i^*$: Fermi energy in the $n^+$ layer, relative to the conduction band edge
- $E_i^*$, $E_i^{*n}$: conduction band edges in the $i$ and $n^+$ layers, respectively
- $\Delta E_i$: conduction band edge offset at the $n^+ - i$ interface
- $\Delta E_d$: donor ionization energy in the $i$ layer
- $F$: electric field in the space charge region
- $h$: Planck constant
- $I_{i,j}$: dark current (density) flowing through the $n^+ - i$ structure
- $I_{th}$: thermionic current (density) determined by the interfacial workfunction
- $k$: Boltzmann constant
- $L_i$: electron scattering length in the $i$ layer
- $M$: number of equivalent minima in the conduction band
- $m_e$: density-of-state effective mass for electrons
- $m_0$: electron rest mass
- $N_c$, $N_w$: effective density of states in the conduction band
- $N_c^*$, $N_w^*$: donor and acceptor concentrations in the $i$ layer, respectively
- $N_d$: ionized donor concentration in the $i$ layer
- $N_e$: doping concentration in the emitter ($n^+$) layer
- $n$: electron concentration in the space charge region
- $n_e$: electron concentration in the bulk of the $i$ layer
- $n_i$: electron concentration at the $n^+ - i$ interface
- $n_i^*$: electron concentration when the Fermi level coincides with the donor level
- $q$: electron charge
- $T$: temperature
- $v$: electron potential in the space charge region
- $V_b$: applied bias voltage
- $V_{fb}$: flat-band voltage
- $W_i$: thickness of the emitter layer
- $W_{x}$: width of the space charge region
- $x_m$: distance from the interface barrier-maximum position relative to the interface
- $\Delta$: interface workfunction
- $\Delta_0$: total interfacial barrier height
- $\epsilon_r$: permittivity in vacuum
- $\epsilon_r$: relative dielectric constant of semiconductor
- $\eta$: quantum efficiency of the detector
- $\eta_i$: photon absorption efficiency
- $\eta_e$: barrier collection efficiency
- $\eta_i$: internal quantum efficiency
- $\eta_c$: cutoff wavelength of the detector
- $\mu$: drift mobility for electrons
- $\phi$: energy band bending in the space charge region
- $\phi_{eq}$: barrier height due to the space charge effect at equilibrium
- $\phi_{max}$: barrier height due to the space charge effect at the barrier-maximum position

1. INTRODUCTION

Far-infrared (FIR) detectors and arrays with the cutoff wavelength ($\lambda_c$) ranging from a few tens to a few hundreds of $\mu$m are critically needed for FIR spectroscopy and FIR remote sensing in space. In recent years, there has been a strong interest in a novel Si homojunction interfacial workfunction internal photoemission (HIWIP) FIR detector[1–5]. The detector operation is based on internal photoemission occurring at the interface between a heavily doped absorber/emitter layer ($n^+$) and a lightly doped (or intrinsic) layer ($n^+ - i$). The interfacial barrier height, which depends on the emitter layer doping concentration ($N_e$) and applied bias, will determine the $\lambda_c$. This detector concept was first proposed and demonstrated on forward biased commercial Si $p-i-n$ diodes operated at 4.2 K[1], and
different $\lambda_s$ in the range of 30–220 $\mu$m were obtained[2,3]. Theoretical modeling of the detector performance, such as $\lambda_s$, spectral response, quantum efficiency, dark current, and noise equivalent power (NEP), has been performed in our recent work[4,5]. It is shown that HIWIP FIR detectors may have a performance comparable to that of conventional Ge FIR (unstressed and stressed) photoconductors[6] and Ge blocked-impurity-band detectors[7], with a unique material advantage over them. It is noted that the photodetection mechanism of HIWIP FIR detectors is similar to that of Schottky-barrier-type detectors, such as PtSi/Si detectors[8] and Ge, Si$_{1-x}$/Si heterojunction detectors[9], in spite of the differences in the response wavelength range, operating temperature, and interfacial barrier formation mechanism.

Due to the free carrier "spill over" from the emitter to the $i$ layer, a space charge region near the interface is created in the $i$ layer, which was not treated in our previous detector performance analyses. This space charge, consisting of excess mobile electrons and fixed ionized impurities, will modify the interfacial barrier shape and thus affect the detector design. Up to now, several analytical and numerical approaches have been proposed, with different assumptions and simplifications, to describe the electrostatic and current transport properties of high–low junctions and $n-i-n$ (or $p-i-p$) structures. Ludman and Silverman[10] presented a numerical method to describe the equilibrium properties of abrupt high–low junctions (where the heavily doped side is degenerate) at low temperatures with application to extrinsic Si photoconductors. Recently, Kuznicki[11] developed an analytical model to solve the same problem for the non-degenerate case. An exact theory, describing the space charge and potential distributions as well as the space-charge-limited current for both equilibrium and applied bias cases, is based on the solutions to the Poisson equation and the drift–diffusion equation with proper boundary conditions. Schmidt and Henisch[12] presented a numerical method for non-degenerate $n-i-n$ (or $p-i-p$) structures, taking into account the $i$ layer doping properties and using a constant interface carrier concentration as the boundary condition. Luryi et al.[13,14] developed an analytical theory for the same structures, neglecting the fixed charge due to any residual doping in the $i$ layer and using a more realistic boundary condition of constant quasi-Fermi level. A numerical method similar to that of Ref.[12] has been used by Haegel and White[15] to model the near-contact space charge region for the cooled extrinsic Ge FIR photoconductor, where the implanted contact layer is doped well above the metal-insulator (Mott) transition concentration by several orders of magnitudes.

The purpose of our work is to analyze the space charge effect in low temperature Si HIWIP FIR detectors, in which $N_e$ is above the Mott transition value but below the value at which the interfacial workfunction becomes zero[4]. Our interest is mainly on how the interfacial barrier shape and hence the detector performance (such as the cutoff wavelength, quantum efficiency, dark current, etc.) are affected by the $i$ layer thickness and doping level, in addition to the emitter layer parameters and operating conditions. As the first step in this paper, only an $n^+-i$ structure with a thick $i$ layer is considered, i.e. the role of the collector layer is neglected. In this way, a complete picture for the whole space charge region can be developed. This case is much closer to that of commercial $p-i-n$ diodes, in which the $i$ layer thickness ranges from a few tens of $\mu$m to over 100 $\mu$m. We will basically follow the numerical method used in Refs[12,15], to calculate the distributions of space charge density (including both mobile carriers and fixed ionized impurities), electric field and potential barrier near the interface, and their dependence on the applied bias, temperature, and $i$ layer doping level. The calculated results from this model can effectively explain the previous experimental results obtained from commercial $p-i-n$ diodes.

2. DEVICE STRUCTURE AND OPERATION MECHANISM

The basic structure of a frontside illuminated single layer $n^+-i$ HIWIP FIR detector is shown in Fig. 1. A negative bias voltage relative to the substrate (giving a forward biased condition) is applied. The structure consists of an emitter layer ($n^+$), a lightly doped (or intrinsic) layer ($i$), and a collector layer ($n$). The emitter layer is doped to somewhat above the Mott transition concentration but below that critical value at which the interfacial workfunction becomes zero[4]. The collector layer is moderately doped, so that even at low temperatures it has a relatively low resistivity due to the impurity band conduction, while it is still transparent in the FIR range as the photon energy is smaller than the energy gap separating the impurity band and the conduction band edge. The top and bottom contact layers ($n^++$) are doped much above the Mott transition value to obtain good ohmic

![Fig. 1. Basic structure of frontside illuminated $n^+-i$ HIWIP FIR detector. A thick $i$ layer is assumed in this modeling work.](image-url)
Space charge analysis of Si $n^+ - i$

![Figure 2](image)

Fig. 2. Energy band diagram near the $n^+ - i$ interface. The $i$ layer conduction band edge ($E_F^i$) is represented by dashed line at zero bias and by solid line at external biases.

contacts. The top layer is formed as a ring surrounding the active area to avoid unnecessary absorption losses. The $i$ layer is transparent in the FIR range since the photon energy is smaller than the donor ionization energy.

The incident photons are absorbed in the emitter layer by the free carrier absorption mechanism. Some of the photoexcited electrons are able to escape over the interfacial barrier and finally reach the collector layer. The total quantum efficiency is determined by photoexcitation, emission to the interfacial barrier, hot electron transport, and barrier collection[4]. In order to obtain high internal quantum efficiency, the emitter layer thickness ($d_e$) should be thin. This will reduce the photon absorption efficiency. Thus, an optimal thickness should be found by a tradeoff of photon absorption and hot electron scattering. According to our recent work[4], this optimal thickness ranges from several tens to several hundreds of Å depending on $N_e$ (or required $\lambda_e$).

The energy band diagram of an $n^+ - i$ interface is shown in Fig. 2. Here, the $i$ layer is assumed to be thick enough so that the effect of the collector layer can be ignored. $E_F^i$ is the Fermi energy relative to the conduction band edge in the $n^+$ layer. $E_F$ is the Fermi energy in the bulk of the $i$ layer at thermal equilibrium. $\Delta E_C$ is the conduction band edge offset due to the band-gap narrowing effect in the $n^+$ layer, which increases with increasing $N_e$ and can be calculated using high density theory[4,16]. The interfacial workfunction due to band edge offset is given by $\Delta \phi = \Delta E_C - E_F^i$. The relationship of $\Delta \phi$ vs $N_e$ has been calculated in our recent work[4]. In principle, $\Delta \phi$ can be arbitrarily small by increasing $N_e$. For an ideal case, where all other effects which may modify the interfacial barrier shape are negligible, $\lambda_e$ is determined by $\Delta \phi (\lambda_e = 1.24/\Delta \phi)$. For actual HIWP F IR detectors, $\Delta \phi$ is adjusted in the range from several to a few tens of meV to match the FIR wavelength range. Therefore, the detector must be operated at very low temperatures, from a few to a few tens of K (depending on $\lambda_e$), to reduce the dark current caused by thermal excitation[5].

In fact, there are at least two effects which can modify the interfacial barrier shape. The first is the image force effect, which has been considered in our previous work[4,5]. The second is the space charge effect, which will be considered in this work. The creation of space charge region is due to the large free carrier concentration gradient at the $n^+ - i$ interface, which causes the free carriers in the $n^+$ layer to spill over into the $i$ layer. At equilibrium, the Fermi energy must be at the same level throughout the whole structure. The energy band bending is the balance of the diffusion process and the drift process under the

![Figure 3](image)

Fig. 3. Spatial distributions of (a) electron concentration ($n$) in solid lines and ionized donor concentration ($N_d^+$) in dashed lines, and (b) electric field ($F$) in solid lines and energy band bending ($\phi$) in dashed lines, at zero bias field and different temperatures, with $N_e = 1 \times 10^{17}$ cm$^{-3}$, (1) $T = 5$ K, (2) $T = 15$ K, and (3) $T = 30$ K.
induced electric field which opposes the flow of free carriers. In Fig. 2, the energy band bending is denoted by $\phi(x)$. If the $i$ layer is very thick (longer than the space charge region), then at equilibrium, the barrier height due to space charge effect will be $\phi_b = E_F^i - \Delta_x$, or the total barrier height is $E_F$. In addition to the mobile free carriers, the space charge region also contains some fixed ionized impurities. The $i$ layer, which actually is a lightly doped $n$-type layer in our case, unavoidably contains some fully ionized compensating acceptors. In the bulk of the $i$ layer, the ionized donor concentration ($N_d^i$) and free electron concentration. At very low temperatures, $N_d^i = N_w$. In the space charge region, some ionized donors will be neutralized by the excess free electrons coming from the $n^+$ layer, resulting in a distribution of fixed negative space charge. The electrons at the interface available for diffusion are those which are thermally excited with an energy sufficiently large to overcome the interfacial workfunction $\Delta_x$. So, the electron concentration at the interface ($n_0$) has a strong temperature dependence.

With the application of a negative bias field $F_n$, a barrier maximum is formed as shown in Fig. 2. At the barrier-maximum position, the electric field, $F(x)$, in the space charge region, changes from positive to negative. In the bulk of the $i$ layer, $F(x)$ approaches $F_n$, and the free electron concentration and the ionized donor concentration approach their equilibrium values. Both barrier height ($\phi_b$) and barrier-maximum position ($x_{max}$) will decrease with increasing $F_n$.

It is worthwhile to notice the difference between barriers in homojunction barrier detectors (HBD) with a thick $i$ layer and those in Schottky-barrier-type detectors (SBD). In the case of SBD, the space charge is composed mainly of fixed ionized impurities with few free carriers. So the barrier is a high-resistance depletion region. The barrier height is solely determined by the interfacial workfunction, and the barrier-maximum position will be at the interface, if the image-force effect is neglected. The externally applied bias appears mainly across the barrier region, and the dark current flowing through the device structure is limited by the barrier. In the case of HBD with a thick $i$ layer, the space charge region is full of excess free carriers, especially in the region near the interface. Thus, it is a low-resistance region compared with the bulk of the $i$ layer. The space charge causes a large increase in the barrier height. The externally applied bias appears mainly across the bulk of the $i$ layer. The dark current is limited by the bulk resistivity of the $i$ layer, and the $n^+ - i$ interface acts as an ohmic contact. In addition, the SBD can operate at zero bias because the built-in electric field enhances the flow of photoexcited carriers. On the other hand, for the HBD with a thick $i$ layer the electric field opposes the flow of photoexcited carriers at zero bias. So a negative bias to the $n^+$ region, which gives a forward biased structure, must be applied to make the HBD work. Also, the barrier-maximum position of the HBD is not at the interface, which reduces the barrier collection efficiency and hence the quantum efficiency[4].

### 3. THEORETICAL MODEL

The space charge distribution under steady state can be obtained by simultaneously solving the drift–diffusion equation:

$$ j = q\mu_e n(x) \frac{dv}{dx} + qD_e \frac{dn}{dx}, \quad (1) $$

and the Poisson equation

$$ \frac{d\varphi}{dx} = \frac{q}{\epsilon_0 \epsilon_i} [n(x) - N_d^i(x) + N_w], \quad (2) $$

where $j$ is the current density, $n(x)$ the free electron concentration, $v(x)$ the electron potential, $N_d^i(x)$ the ionized donor concentration, $N_w$ the compensating acceptor concentration which depends on material growth, and $\epsilon_i$ the relative dielectric constant. $\mu_e$ and $D_e$ are the drift mobility and diffusion coefficient for electrons, which are related by the Einstein relation $D_e = (kT/q)\mu_e$.

At steady state, $N_d^i$ can be derived from the principle of detailed balance for thermal carrier...
generation and recombination:

\[ N^+_D(x) = \frac{n_1 N_{n_i}}{n_1 + n(x)} \]  

(3)

where \( N_{n_i} \) is the total donor concentration in the \( i \) layer, and \( n_1 \) is the electron concentration when the Fermi level coincides with the donor level, and is given by \( n_1 = (N_e/2) \exp(-\Delta E_i/kT) \). Here, \( \Delta E_i \) is the donor ionization energy, \( N_e = 2(2\pi m_e kT/h^2)^{3/2} M_e \) the conduction band effective density of states, \( m_e \) the electron density-of-state effective mass, and \( M_e \) the number of equivalent minima in the conduction band. For Si, \( m_e = 0.33 m_0 \) and \( M_e = 6 \). The equilibrium values of \( N_D^+ \) and the electron concentration in the bulk of the \( i \) layer \( (n_b) \) are related by \( N_D^+ = N_{n_i} + n_b \). Together with eqn (3), we obtain

\[ n_b = \frac{[(N_{n_i} + n_1)^2 + 4n_1(N_{n_i} - N_{n_i})]^1/2 - N_{n_i} - n_1}{2} \]  

(4)

The Fermi energy in the bulk of the \( i \) layer is given by \( E_F^i = kT \ln \left( N_{n_i}/n_b \right) \).

Combining eqns (1) and (2), we get a second-order non-linear differential equation for \( n \):

\[ \frac{d^2 n}{dx^2} + \frac{1}{q n} \left( j - qD_e \frac{dn}{dx} \right) \frac{dn}{dx} - \frac{q\mu_n n}{\epsilon_0 \epsilon_r} \left( n - \frac{n_1 N_{n_i}}{n_1 + n_1} + N_{n_i}\right) = 0 \]  

(5)

where the current density \( j \) is a constant at steady state, and becomes a pure drift current in the bulk of the \( i \) layer. So, we have

\[ j = q\mu_n n_b F_b \]  

(6)

Actually, \( j \) is the dark current density flowing through an ideal \( n^+ - i \) detector with a thick \( i \) layer.

The boundary conditions are given by

at \( x = 0 \), \( n = n_0 = N_{n_i} \exp(-\Delta E_i/kT) \),

at \( x \to \infty \), \( n \to n_b \).

In this work, we have neglected all tunneling effects since we assume a thick barrier is associated with our case. Also, we have assumed that the electron concentration at the interface \( (n_b) \) is not modified by the applied bias field. This is a valid approximation for long base structures[17] since \( j \) is much smaller than the thermionic emission current \( (J_{th}) \), which is determined by the interfacial work function. \( J_{th} \) is the temperature-limited saturation current which can be drawn from the emitter.

Equation (5) has been numerically solved by using the "shooting method". In this process, one first assumes an initial value for \( dn/dx \) at \( x = 0 \) and solve the equations. Then, this initial value is adjusted iteratively until \( n \to n_b \) as \( x \to \infty \). In order to get solutions which are stable over long distances, \( n'(0) \) must be fixed with high precision[18]. This work, the program is written in quadri-precision, which is accurate to 34 decimal places. With the knowledge of \( n(x) \), the corresponding distributions of band bending, \( \phi(x) = -qV(x) \), and electric field, \( F(x) = -dn/dx \), can be obtained from eqn (1) and \( N_D^+ \) is obtained from eqn (3). As \( x \to \infty \), \( F \to F_h \), and \( \phi \to \phi_b \) at zero bias, as shown in Fig. 2.

4. RESULTS AND DISCUSSION

Using the above equations, we have calculated the distributions of free electron concentration, ionized donor concentration, electric field, and energy band bending for a Si \( n^+ - i \) structure with a thick \( i \) layer. The dependence of these distributions on bias field, temperature, and compensating acceptor concentration is shown. Unless indicated otherwise, the following parameters were fixed in the calculation: \( N_c = 1 \times 10^{19} \text{ cm}^{-3} \) (corresponding to \( \Delta E_a = 11.1 \text{ meV} \)), \( N_{n_i} = 1 \times 10^{15} \text{ cm}^{-3} \), and \( \Delta E_i = 45.0 \text{ meV} \).

Figure 3(a) shows the spatial distributions of electron and ionized donor concentrations at zero bias field and different temperatures \( (T = 5, 15, \text{ and } 30 \text{ K}) \), with \( N_{n_i} = 1 \times 10^{15} \text{ cm}^{-3} \). The corresponding spatial distributions of electric field and band bending are shown in Fig. 3(b). At \( T = 5, 15, \text{ and } 30 \text{ K} \), \( n \) is \( 4.2 \times 10^5, 6.0 \times 10^5 \), and \( 1.2 \times 10^6 \text{ cm}^{-1} \) at the interface, and reduces to the equilibrium values of \( 1.4 \times 10^{-21}, 1.2 \times 10^4 \), and \( 1.1 \times 10^{15} \text{ cm}^{-3} \) in the bulk of the \( i \) layer, respectively. The values of \( N^+_D \) are \( 3.3 \times 10^{-22}, 2.0 \times 10^4 \), and \( 1.0 \times 10^6 \text{ cm}^{-3} \) at the interface, respectively, and increase to the acceptor concentration \( 1 \times 10^{11} \text{ cm}^{-3} \) in the bulk of the \( i \) layer. Within this temperature range, the width of the

Fig. 5. Spatial distributions of (a) electron concentration \( n \) in solid lines and ionized donor concentration \( N^+_D \) in dashed lines, and (b) electric field \( (F) \) in solid lines and energy band bending \( (\phi) \) in dashed lines, at \( T = 20 \text{ K} \) and \( N_{n_i} = 1 \times 10^{15} \text{ cm}^{-3} \), for different bias field values. (1) \( F_b = 0 \text{ V cm}^{-1} \), (2) \( F_b = -30 \text{ V cm}^{-1} \), and (3) \( F_b = -300 \text{ V cm}^{-1} \).
space charge region is about 2.5–3 \( \mu \text{m} \). It is noted that the bulk electron concentration is much smaller than the acceptor concentration at these temperatures.

The barrier heights due to the space charge effect are 32.2, 28.9, and 24.1 meV at 5, 15, and 30 K, respectively. The electric field distribution in the space charge region is characterized by three regimes, as shown by solid curve 2 (\( T = 15 \text{ K} \)) in Fig. 3(b). In the first region, the space charge closest to the interface is dominated by free electrons, and \( F \) is large and rapidly decreasing. In the second (middle) region, the space charge is approximately constant and is given by the acceptor concentration, since both \( n \) and \( N_{a}^{+} \) are much smaller than \( N_{a}^{+} \). So, \( F \) decreases linearly, with a slope proportional to \( N_{a}^{+} \), which is a result of eqn (2). Finally, in the third region, as \( N_{a}^{+} \) approaches \( N_{a}^{+} \), the slope is given by \( N_{a}^{+} - N_{a}^{+} \) and \( F \) goes to zero as the equilibrium bulk condition \( N_{a}^{+} = N_{a}^{+} \) is reached. This feature was first described by Haegel and White[15] for the near-contact region in cooled Ge photoconductors. From Fig. 3(b), we can also see that at \( T = 5 \text{ K} \) (solid curve 1) only regions 2 and 3 exist, since \( n_{e} \) is much smaller than \( N_{a}^{+} \) at lower temperatures. While at \( T = 30 \text{ K} \) (solid curve 3) only regions 1 and 3 exist, since even in the middle region \( n_{e} \) is still larger than \( N_{a}^{+} \) at higher temperatures.

Figure 4(a) shows the spatial distributions of electron and ionized donor concentrations at zero bias field and \( T = 10 \text{ K} \), for different compensating acceptor concentrations (\( N_{a} = 1 \times 10^{11}, 1 \times 10^{12}, \) and \( 1 \times 10^{13} \text{ cm}^{-2} \)). The corresponding spatial distributions of electric field and band bending are shown in Fig. 4(b). As \( N_{a} \) decreases, the width of the space charge region (\( W_{a} \)) and the equilibrium bulk electron concentration (\( n_{e} \)) increase, while the electric field at the interface (\( F_{0} \)) and the barrier height (\( \phi_{b} \)) decrease.

![Fig. 6. Temperature dependence of barrier height (solid lines) and barrier-maximum position (dashed lines) at \( F_{0} = -1000 \text{ V cm}^{-1} \), for two different compensating acceptor concentrations. (1) \( N_{a} = 1 \times 10^{11} \text{ cm}^{-3} \) and (2) \( N_{a} = 1 \times 10^{11} \text{ cm}^{-3} \).](image1)

![Fig. 7. Bias field dependence of total barrier height \( \Delta \) (solid lines) and \( x_{m} \) (dashed lines) calculated for \( N_{a} = 1 \times 10^{11} \text{ cm}^{-3} \) at \( T = 4.4 \) and 30 K. The experimental data (+) of barrier height are obtained from the spectral response measured for a \( p-i-n \) diode at liquid helium temperature.](image2)

For \( N_{a} = 1 \times 10^{11}, 1 \times 10^{12}, \) and \( 1 \times 10^{13} \text{ cm}^{-3} \), \( W_{a} = 2.5, 8, \) and 28 \( \mu \text{m} \), \( n_{e} = 1.8 \times 10^{-4}, 1.8 \times 10^{-3}, \) and \( 1.8 \times 10^{-2} \text{ cm}^{-3} \), \( F_{0} = 90, 92, \) and 30 V cm\(^{-1} \), and \( \phi_{b} = 30.6, 28.6, \) and 26.6 meV, respectively.

Figure 5(a) shows the spatial distributions of electric field and ionized donor concentrations at \( T = 20 \text{ K} \) and \( N_{a} = 1 \times 10^{13} \text{ cm}^{-3} \), for different bias field values (\( F_{0} = 0, -30, \) and \( -300 \text{ V cm}^{-1} \)). The corresponding spatial distributions of electric field and band bending are shown in Fig. 5(b). With the application of an external bias, a net drift field is created which results in a constant current flow throughout the detector. For a negative bias, the electric field in the space charge region will change from positive to negative at a certain distance from the interface. This boundary marks a transition from diffusion-dominated to drift-dominated current flow. The point at which \( F = 0 \) is the point of pure diffusion current, which corresponds to a barrier maximum. As \( F_{0} \) increases, both barrier height (\( \phi_{b} \)) and barrier-maximum position (\( x_{m} \)) decrease, and the width of the space charge

![Fig. 8. Bias field dependence of dark current calculated for \( N_{a} = 1 \times 10^{13} \text{ cm}^{-3} \) and \( N_{a} = 1 \times 10^{13} \text{ cm}^{-3} \) at different temperatures. The experimental data (●) are from another \( p-i-n \) diode measured at about 13 K.](image3)
region \((W_n)\) increases. As can be seen from Fig. 5, at zero bias field, \(\phi_0 = 27.2\) meV and \(W_n = 3\) \(\mu\)m. At \(F_s = -30\) and \(-300\) \(\text{V cm}^{-1}\), \(\phi_m = 25.5\) and 22.4 meV, \(x_m = 2.0\) and 1.7 \(\mu\)m, and \(W_u = 3.5\) and 7 \(\mu\)m, respectively.

Figure 6 shows the temperature dependence of barrier height \((\phi_h)\) and barrier-maximum position \((x_m)\) at \(F_s = -1000\) \(\text{V cm}^{-1}\), for two different compensating acceptor concentrations \((N_a = 1 \times 10^{13}\) and \(1 \times 10^{15}\) \(\text{cm}^{-3}\)). The temperature dependence of \(\phi_h\) is similar to that of the Fermi energy \(E_F\). As the temperature decreases, \(\phi_h\) first decreases and then increases after going through a minimum. As \(N_u\) decreases, the whole \(\phi_m\) curve lowers, with the largest lowering taking place around the minimum barrier height \(\phi_m\) (min). Also, the minimum temperature \(T_m\) decreases with the decrease of \(N_u\). For \(N_u = 1 \times 10^{13}\) and \(1 \times 10^{15}\) \(\text{cm}^{-3}\), \(T_m = 31\) and 25 K, and \(\phi_m\) (min) = 15.8 and 12.6 meV, respectively. In contrast, \(x_m\) increases monotonically with the decrease of temperature and has the following features. In the higher temperature range, \(x_m\) has a weak temperature dependence; near to \(T_m\), \(x_m\) begins to increase more rapidly with the further decrease of \(T\); in the lower temperature range, the change of \(x_m\) becomes slower again. In addition, in the higher temperature range, \(N_a\) has almost no effect on \(x_m\). While in the lower temperature range, \(x_m\) increases significantly with the decrease of \(N_u\). We note that in the temperature range of 23–36 K, the \(x_m\) for \(N_u = 1 \times 10^{15}\) \(\text{cm}^{-3}\) is even smaller than that for \(N_u = 1 \times 10^{13}\) \(\text{cm}^{-3}\).

Figure 7 shows the bias field dependence of total barrier height, \(\Delta = \Delta_0 + \phi_m\), and \(x_m\) for \(N_u = 1 \times 10^{13}\) \(\text{cm}^{-3}\), at \(T = 4.4\) and 30 K. It can be seen that the reduction of both \(\Delta\) and \(x_m\) with the increase of \(F_s\) is more prominent in the high temperature range than in the low temperature range. At \(T = 4.4\) K, \(\Delta\) decreases from 43.5 meV at zero bias to 41.8 meV at \(F_s = -1000\) \(\text{V cm}^{-1}\), and \(x_m\) decreases from 2.29 \(\mu\)m at \(F_s = -5\) \(\text{V cm}^{-1}\) to 2.01 \(\mu\)m at \(F_s = -1000\) \(\text{V cm}^{-1}\). At \(T = 30\) K, \(\Delta\) decreases from 35.2 meV at zero bias to 26.9 meV at \(F_s = -1000\) \(\text{V cm}^{-1}\), and \(x_m\) decreases from 1.88 \(\mu\)m at \(F_s = -5\) \(\text{V cm}^{-1}\) to 0.53 \(\mu\)m at \(F_s = -1000\) \(\text{V cm}^{-1}\). This difference is easy to understand. Under the same bias field, the steady-state current is much larger at higher temperatures than at lower temperatures. As a result, the barrier-maximum position must be closer to the interface at higher temperatures than at lower temperatures, so that the same current value can be maintained at \(x_m\), where \(j\) becomes a pure diffusion current and increases as \(x_m\) decreases. As \(x_m\) decreases, \(\phi_m\) will decrease correspondingly. The temperature dependence of \(x_m\) shown in Fig. 6 can also be understood similarly. Also shown in Fig. 7 are a set of data points, which was obtained from the cutoff wavelengths of a commercial Si \(p-i-n\) diode measured for different biases at liquid helium temperature. The bias field is derived from \(F_s = (V_b - V_i)/W_i\), where \(V_b\) is the applied voltage, \(V_i = 1.11\) V the flat-band voltage for Si[1], and \(W_i = 16\) \(\mu\)m the \(i\) layer thickness of the \(p-i-n\) diode. It is seen that these data points are in good agreement with the \(\Delta - F_s\) curve at 4.4 K.

The influence of the emitter layer doping concentration on \(\Delta\) and \(x_m\) is also investigated. It is found that \(\Delta\) is independent of \(N_e\) (and hence \(\Delta_0\)), while \(x_m\) increases with increasing \(N_e\). For example, for \(N_e = 1 \times 10^{19}\) \(\text{cm}^{-3}\) and \(T = 4.4\) K, when \(N_e\) increases from \(1 \times 10^{19}\) \(\text{cm}^{-3}\) to \(5 \times 10^{19}\) \(\text{cm}^{-3}\) (correspondingly, \(\Delta_0\) decreases from 11.1 meV to 2.4 meV), \(x_m\) increases from 2.01 to 2.28 \(\mu\)m.

Above results show that for an \(n^- - i\) detector with a thick \(i\) layer, the space charge effect can cause a significant increase of the interfacial barrier height. The total barrier height \(\Delta\), which determines the \(\lambda_c\) of the detector spectral response, can be rather large, even if the \(n^-\) layer is doped above the Mott transition concentration and \(\Delta_0\) becomes very small. Depending on the doping level in the \(i\) layer, applied bias, and temperature, \(\Delta\) can be in the range of a few tens of meV. This is in agreement with previous experimental results obtained from a large part of commercial Si \(p-i-n\) diodes measured. The \(\lambda_c\) observed from these diodes are in the range of 30–60 \(\mu\)m[1–3], which corresponds to \(\Delta = 20–41\) meV. On the other hand, it is known[4] that the total quantum efficiency of a HiWIP detector is the product of the photon absorption efficiency \((\eta_g)\), internal quantum efficiency \((\eta_i)\), and barrier collection efficiency \((\eta_c)\), where \(\eta_c = \exp(-x_m/L_i)\), with \(L_i\) being the electron scattering length in the \(i\) layer. \(L_i\) is estimated to be around a few hundreds of \(\lambda\) at low temperatures, which is mainly due to electron–phonon scattering. The barrier-maximum position \((x_m)\) obtained from the above model ranges from a few thousands of \(\lambda\) to several \(\mu\)m, depending on the device parameters and operating conditions. So, \(\eta_c\) can be as small as \(10^{-3}\) or even smaller. This may partly explain why commercial \(p-i-n\) diodes usually show a very low quantum efficiency.

From this model, we see that for an \(n^- - i\) detector with a thick \(i\) layer, the dark current \((I_d)\) has a linear dependence on the bias field (or voltage), as given by eqn (6). This is in good agreement with previous experimental results obtained from commercial \(p-i-n\) diodes[1]. Figure 8 shows the \(I_d - F_s\) curves calculated for different temperatures, together with the experimental data for a \(p-i-n\) diode measured at about 13 K, which are taken from Ref[1]. The junction area and \(i\) layer thickness of this diode are \(1 \times 10^{-2}\) \(\text{cm}^2\) and 50 \(\mu\)m, respectively. A good fitting to the experimental data is obtained at 13 K by assuming \(N_a = 1 \times 10^{14}\) \(\text{cm}^{-3}\), \(N_u = 1 \times 10^{13}\) \(\text{cm}^{-3}\), and \(\mu_e = 1 \times 10^{3}\) \(\text{cm}^2\text{V}^{-1}\text{s}^{-1}\). Here, a constant electron drift mobility is assumed in the calculation, since in the low temperature range \((T < 25\) K \(\mu_e\) is mainly limited by neutral impurity scattering, a temperature insensitive elastic process, as demonstrated by experiments[19]. At \(T = 10, 13,\) and 20 K, the thermionic
emission currents ($I_n$) determined by $\Delta n = 11.1$ meV are, $I_n = 6.6 \times 10^{-5}$, $2.0 \times 10^{-3}$, and $1.6 \times 10^{-4}$ A, respectively. It is seen that the corresponding dark currents determined by the bulk conduction in the $i$ layer are much smaller than $I_n$ in the bias field range of interest.

From above results, we see that the space charge existing in the near-interface region has, at least, two harmful effects on the performance of an $n^+\cdots-i$ detector with a thick $i$ layer. 

(1) $\lambda_n$ becomes much shorter than that determined by $\Delta n$, and is almost independent of $N_n$, only determined by the $i$ layer doping level, temperature, and applied bias. 

(2) $\eta$ is reduced significantly due to the shift of the barrier maximum away from the interface.

These effects are undesirable for the operation of actual HIWIP FIR detectors[4]. To avoid these disadvantages, a thin $i$ layer, with thickness much smaller than the width of the space charge region, is needed. It is expected that the interaction between the emitter contact and the collector contact will lead to a much lower barrier height, with the barrier maximum much closer to the emitting interface at a given bias. Obviously, the values of $\Delta$ and $x_m$ will depend on the $i$ layer thickness and the doping concentrations in each of these layers (emitter, $i$, and collector) and decrease with decreasing $W_i$. Accordingly, the dark current will become space-charge-limited and increase with the decrease of $W_i$. Finally, below some value of $W_i$, $I_n$ will be limited by the interfacial barrier, since the space-charge-limited current may exceed the barrier-limited injection current, while $\lambda_n$ may be determined mainly by $\Delta n$. On the other hand, as suggested before[1,4], a higher effective quantum efficiency is expected for the detector with a multilayer structure ($n^+\cdots-i\cdots-n^+\cdots$), due to the increased photon absorption efficiency and possible photocurrent gain enhancement. Thus, a thin $i$ layer is also essential for the realization of multilayer detectors, which can be fabricated by MBE or MOCVD growth technologies. In order to obtain a complete understanding of the space charge effect in the thin $i$ layer detector, which is more like an actual HIWIP FIR detector, further work is needed.

5. CONCLUSIONS

According to our calculations, for a Si $n^+\cdots-i$ HIWIP detector with a thick $i$ layer, the width of the space charge region near the interface can be between a few to a few tens of $\mu$m, mainly depending on the compensating acceptor concentration in the $i$ layer, as well as on the bias field, temperature, and other device parameters. At zero bias (equilibrium state), the barrier height ($\Delta$) is equal to the Fermi energy in the bulk of the $i$ layer. Under negative bias fields, $\Delta$ decreases, but is still a few tens of meV. The barrier-maximum position ($x_m$), relative to the emitting interface, ranges from a few thousands $\AA$ to several $\mu$m. Both $\Delta$ and $x_m$ decrease with increasing $F_i$ and depend on temperature and the doping level in the $i$ layer. In the applied bias range of interest, a linear relationship of dark current vs base field (voltage) is expected, with the current value much smaller than the thermionic emission current limited by $\Delta n$. Previous experimental results obtained from commercial Si $p-i-n$ diodes have been well explained using our calculated results. One important conclusion of this work is that in order to minimize the modification to interfacial barrier by the space charge effect, a thin $i$ layer with the thickness much smaller than the width of the space charge region is required for the operation of the actual HIWIP FIR detector. In this way, high detector performance is still expected, as we showed in the previous work[4,5].

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REFERENCES