Aust. J. Phys., 1992, **45**, 781–7

Determination of Barrier Height and Doping Density of a Schottky Diode from Infrared Photoresponse Measurements

Vincent W. L. Chin[A] *and Stephen M. Newbury*[B]

School of Physics, University of New South Wales,
P.O. Box 1, Kensington, Macquarie University, N.S.W. 2033, Australia.
[A] Present address: Semiconductor Science and Technology Laboratories,
Department of Physics, N.S.W. 2109, Australia.
[B] Present address: Research Foundation, University of Lowell,
450 Aiken Street, Lowell, MA 01854, U.S.A.

Abstract

The impurity doping concentration of a semiconductor is commonly determined by measuring the C–V profile of a Schottky diode. In this work, an alternative method is utilised to determine the impurity doping density of a moderately acceptor-doped Schottky diode using infrared photoelectric measurements. Due to the image lowering effect, the barrier is lowered with the increasing field or reverse bias. Having determined the relationship between the reverse bias and the lowered barrier, the doping density and the zero bias barrier height from the infrared photoresponse measurements can be accurately determined. The zero field barrier height can also be evaluated once the doping density and the zero bias barrier height are known. The method developed here can also be utilised to determine the doping profiles of Schottky barrier diodes made from n-type semiconductor.

1. Introduction

The doping density of the semiconductor substrate (both n-type and p-type) of a metal–semiconductor rectifying contact or Schottky barrier diode is usually determined from capacitance–voltage (C–V) measurements (see e.g. Sze 1981; Rhoderick and Williams 1988). In the C–V technique, a small ac voltage is usually superimposed upon a dc bias so that charges of one sign are induced on the metal surface and charges of the opposite sign on the semiconductor, thus enabling the field-ionised impurity concentration in the semiconductor depletion region to be determined by measuring the capacitance as a function of the dc bias. The relationship between capacitance and voltage of the form

$$\frac{1}{C^2} = \frac{2(V_{\rm bi} - V - kT/q)}{q\epsilon_{\rm s} N_i} \tag{1}$$

allows the doping density to be evaluated from the slope of a $1/C^2$ versus V plot. It is given by

$$N_i = \frac{2}{q\epsilon_{\rm s}}\left(\frac{1}{{\rm d}(1/C^2)/{\rm d}V}\right). \tag{2}$$

In equation (1), $V_{\rm bi}$ is the built-in voltage, k the Boltzmann constant, q the electronic charge, $\epsilon_{\rm s}$ the permittivity of the semiconductor, N_i the impurity

0004-9506/92/060781$05.00

doping concentration, and the index i represents either n- or p-type doping. The barrier height can be determined since

$$\phi_{\mathrm{bi}} = V_{\mathrm{bi}} + \xi + kT/q\,, \tag{3}$$

where ϕ_{bi} is the flat-band zero field barrier height and ξ is the depth of the Fermi level.

However, in practice, C–V measurements used to determine the barrier height of the Schottky diode and doping density of substrate can be complicated by various effects. Goodman (1963) reviewed some of the shortfalls of the C–V technique, such as series resistance, traps in the depletion layer, electrical ohmic contact with the semiconductor, an insulating interfacial layer between the metal and semiconductor, to name a few. Furthermore, when the Schottky barrier height is to be determined from devices that have been fabricated with a charge-coupled device (CCD) readout, as is the case with most large-scale focal plane arrays, it is difficult to interpret the C–V results without modelling the effective capacitance of the whole structure.

Thus, the aim of this paper is to describe an alternative and less problematic method as compared with C–V, and to determine the zero bias barrier height and doping density of the substrate of these infrared devices under similar operating conditions of cryogenic temperature, so that the physics of the device can be studied. This is achieved by IR photoresponse measurement.

2. Method of Analysis

The barrier of a Schottky diode is very much field-dependent and thus bias-dependent. The dominant and inevitable field-lowering mechanism is due to image force lowering. The resultant image lowering of the barrier $\Delta\phi$ is given as

$$\Delta\phi = \left(\frac{q\mathcal{E}}{4\pi\epsilon_{\mathrm{s}}'}\right)^{1/2}, \tag{4}$$

where $\mathcal{E}$ is the maximum electric field at the interface and ϵ_{s}' is the permittivity of the semiconductor for image force. Equation (4) is not very useful as it stands since the electric field in the barrier is not known explicitly unless the doping level is known. Thus, it is more desirable to express the electric field as a function of bias voltage and doping density. This can be done by solving the Poisson equation for the system. Under the depletion approximation, the Poisson equation can be integrated and the expression for the electric field as a function of bias and doping is given by

$$\mathcal{E} = \left(\frac{2qN_i}{\epsilon_{\mathrm{s}}}\right)^{1/2}\left(V_{\mathrm{bi}} - V - \frac{kT}{q}\right)^{1/2}, \tag{5}$$

where the term kT/q originates from the contribution of the majority carrier distribution tail. Thus by combining (4) and (5) we get

$$\Delta\phi = \left\{ \frac{q^3 N_i}{8\pi^2 (\epsilon_s)^3} \left(V_{bi} - V - \frac{kT}{q} \right) \right\}^{1/4}, \qquad (6)$$

where ϵ'_s is equated to ϵ_s (Rhoderick and Williams 1988).

From equation (6), for the reverse bias voltage $V_r \gg V_{bi}$, a plot of $V_r^{1/4}$ against ϕ_e (the effective threshold barrier height at a fixed bias) will give a straight line. The slope of this relationship is

$$\frac{d\phi_e}{dV_r^{1/4}} \approx \frac{\Delta\phi}{\Delta V_r^{1/4}} = \left(\frac{q N_i^3}{8\pi^2 (\epsilon_s)^3} \right)^{1/4} \qquad (7)$$

or

$$N_i = \left(\frac{\Delta\phi}{\Delta V_r^{1/4}} \right)^4 \frac{8\pi^2 (\epsilon_s)^3}{q^3}, \qquad (8)$$

and the intercept will give the zero bias barrier height ϕ_{b0}. Once N_i is known, the electric field at zero bias can be calculated from (5) by substituting $V = 0$. Consequently, the image force lowering at zero bias can be evaluated from (4), so that the zero field (flat-band) barrier height can be determined by

$$\phi_{bi} = \phi_{b0} + (\Delta\phi)_{b0}, \qquad (9)$$

if other field-dependent terms at zero bias can be assumed negligible. For low barriers and lightly to moderately doped Si, this assumption is usually valid.

In order to determine the effective barrier height at a fixed reverse bias, the following approach is pursued. The IR photoresponse of a Schottky diode for photon energy greater than the Schottky barrier can be expressed as (Cohen *et al.* 1968)

$$Y = C\left(\frac{(h\nu - \phi_e)^2}{h\nu} \right), \qquad (10)$$

where Y is the quantum yield, C the emission coefficient and $h\nu$ the photon energy. Equation (10) can be expressed in the form

$$\sqrt{Yh\nu} = \sqrt{C}(h\nu - \phi_e). \qquad (11)$$

Hence if $\sqrt{Yh\nu}$ is plotted as function of $h\nu$, a straight line should result with the intercept in the photon energy axis giving the effective barrier height directly. These plots are commonly known as Fowler plots.

3. Experimental Considerations

The CCD Schottky barrier diodes are fabricated on a $\langle 100 \rangle$ p-type Si wafer (with both sides polished) with resistivity of about 10 Ω cm. At 300 K this corresponds to about 1×10^{15} cm^{-3} (Sze 1981). The processing sequence of these CCD Schottky diodes has been detailed elsewhere (Chin 1990; Chin *et al.* 1991*b*).

The IR photoresponse measurements were performed at around 80 K at various reverse biases. The devices were mounted on a dewar with a calcium fluoride window, allowing radiation to pass through. A blackbody source, calibrated with a CI Ltd Model SR400 pyroelectric IR radiometer, was used to illuminate the IR-sensitive Schottky diodes. The diodes were back-illuminated so that energy higher than the bandgap of Si is absorbed by the bulk Si. A set of fixed-frequency narrow-bandwidth interference filters was used to select IR radiation of specific wavelengths. The IR signal chopped at 30 Hz was first fed into a pre-amplifier and then into a Stanford Research system SR510 Lock-in Amplifier. From these measurements, the quantum yields were calculated.

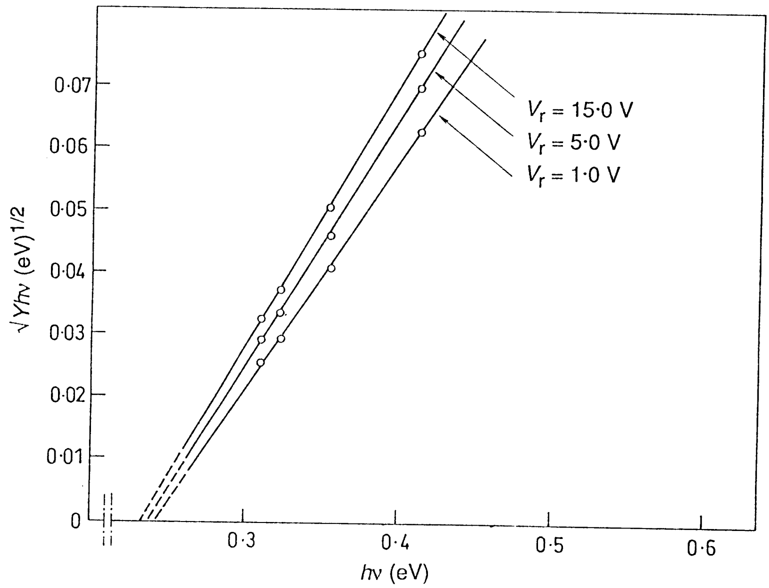

Fig. 1. Fowler plot of the square root of the photoresponse per incident photon versus photon energy for three values of the reverse bias.

Table 1. Effective barrier height as a function of voltage

Voltage (V)	Effective barrier (eV)
0·2	0·245–0·247
0·4	0·244–0·245
0·6	0·243(8)–0·244
1·0	0·243
2·0	0·241
3·0	0·239(5)
5·0	0·237(9)
8·0	0·235(8)
10·0	0·234(8)
15·0	0·232(8)

4. Results and Discussion

To determine the doping level in the substrate of these devices, a series of Fowler plots were made for different bias voltages and the effective barrier height was extracted. Fig. 1 show such a plot with three different reverse biases. Due to image force lowering, it is obvious that the quantum yield increases with reverse bias. In Table 1, the effective barrier height as a function of the applied bias is listed. According to equation (7), a plot of ϕ_e against $V^{1/4}$ will give a linear relationship and the slope can be used to evaluate the doping level of the substrate according to (8), as illustrated in Fig. 2. From the slope in Fig. 2, an acceptor density of $3 \cdot 0 \times 10^{14}$ cm^{-3} is obtained, a value slightly lower than the starting doping level. This is not unreasonable because of two mechanisms. First, these Schottky devices operate near liquid nitrogen temperature and, consequently, some of the impurities may have been 'frozen out', effectively reducing the impurity doping density. According to Pierret (1987), for an impurity density of $N_D \approx 10^{15}$ cm^{-3} the value of N_D^* is actually 5×10^{14} cm^{-3} at 77 K (although ionisation may be higher in the depletion region where the electric field may be sufficient to ionise impurities). Second, a series of silicon dioxide (SiO_2) steps are required in the CCD processes. Since boron (p-doped impurity) is more soluble in SiO_2 than in Si, some of the boron will diffuse into SiO_2 thus depleting the boron in Si, a process known as 'segregation'. Hence, it is not unexpected that the doping density is less than the starting density of 10^{15} cm^{-3}. Furthermore, doping concentrations are usually accurate to within a factor of 2 or 3 of the stated doping; in this regard, the doping concentration determined by this alternative method can be considered good, even if the boron (p-doped) is not depleted from Si as is the case here.

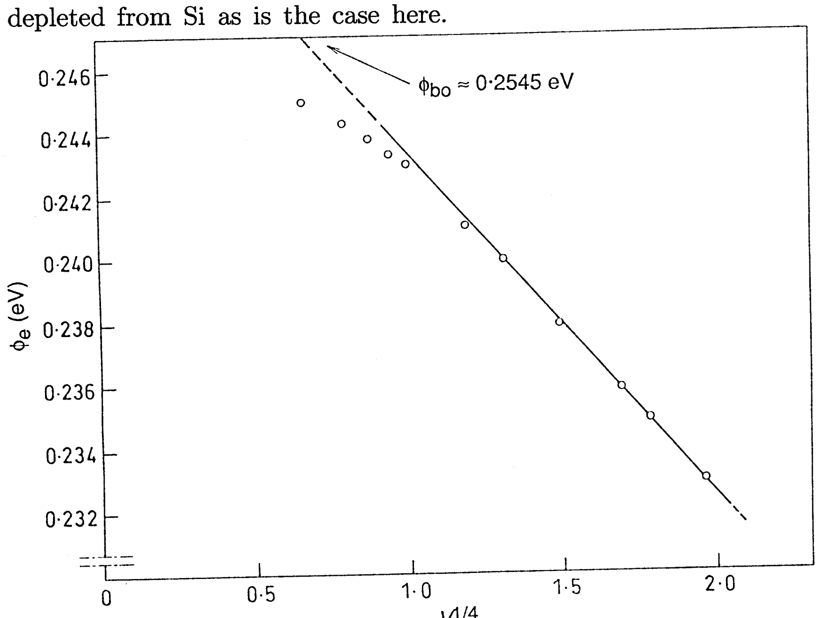

Fig. 2. Plot of the effective barrier height as a function of $V^{1/4}$.

From the intercept of Fig. 2, a zero bias barrier height ϕ_{b0} of $0 \cdot 2545$ eV is obtained which is in excellent agreement with the height obtained from forward *I–V–T* measurements (Chin *et al.* 1991*a*). The calculated value of the flat-band zero field barrier height is $0 \cdot 262$ eV, in good agreement with that obtained from an analytical expression relating the zero bias barrier height and the diode ideality factor in the forward bias (Chin *et al.* 1989) and reverse bias measurements (Chin *et al.* 1990).

In Fig. 2 it is also observed that the linear relationship becomes less correlated at low reverse bias. This is because when V_r approaches V_{bi} equation (7) becomes invalid. In reality, a plot of $(V_{bi}-V-kT/q)^{1/4}$ against effective barrier height gives a linear relationship even at $V \approx V_{bi}$. However, for V_{bi} we require knowledge of the doping density since it can be expressed as

$$V_{bi} = \phi_{bi} - \xi - kT/q\,, \tag{12}$$

where the depth of the Fermi level is

$$\xi = \frac{kT}{q} \ln \frac{N_v}{N_i}\,, \tag{13}$$

and where N_v is the density of states in the valence band. To verify that the deviation from a straight line is due to $V_r \approx V_{bi}$ at low field, a plot of the effective barrier height as a function of $(V_{bi}-V-kT/q)^{1/4}$ is given in Fig. 3 using the parameters determined above. The slight deviation is now apparent.

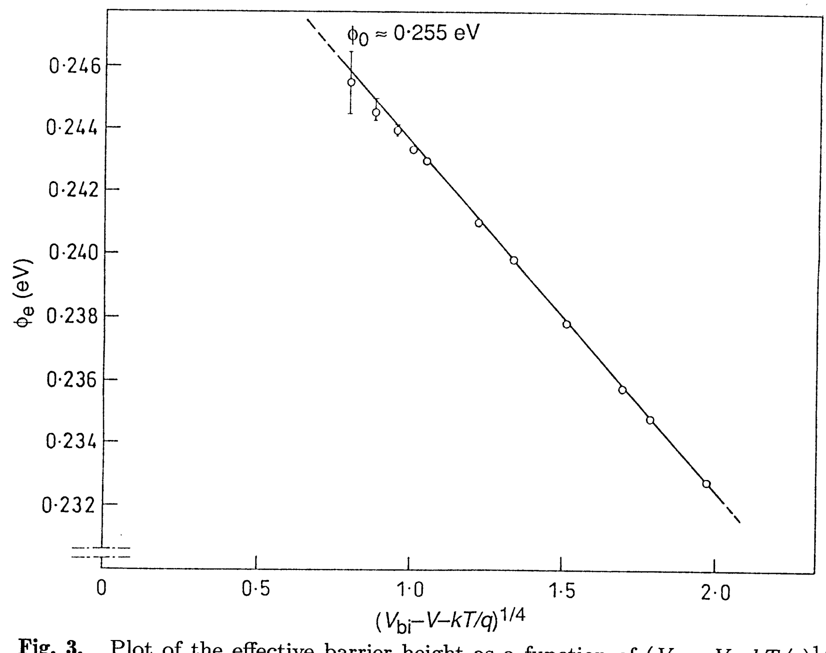

Fig. 3. Plot of the effective barrier height as a function of $(V_{bi}-V-kT/q)^{1/4}$.

5. Summary

Using IR photoresponse measurements, an alternative method is described to determine the doping density and barrier height of CCD Schottky barrier structures, thereby avoiding difficulties associated with C–V measurements. The doping density determined from p-type PtSi CCD Schottky diodes is slightly lower than the starting level. However, by considering the processing sequence of the CCD and the temperatures at which the Schottky devices are operating, where the impurity dopants begin to freeze out, the slightly lower value of impurity doping can be anticipated. Furthermore, the zero field barrier height is in remarkable agreement with that reported elsewhere.

Acknowledgments

We would like to acknowledge helpful discussions with Professor M. A. Green. We would also like to thank Ulrich Theden for fabricating the devices and Professor T. L. Tansley for his encouragement and support. This work is supported by the Australian Research Council and the Defence Research Centre, Salisbury.

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Manuscript received 17 July, accepted 23 September 1992