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.

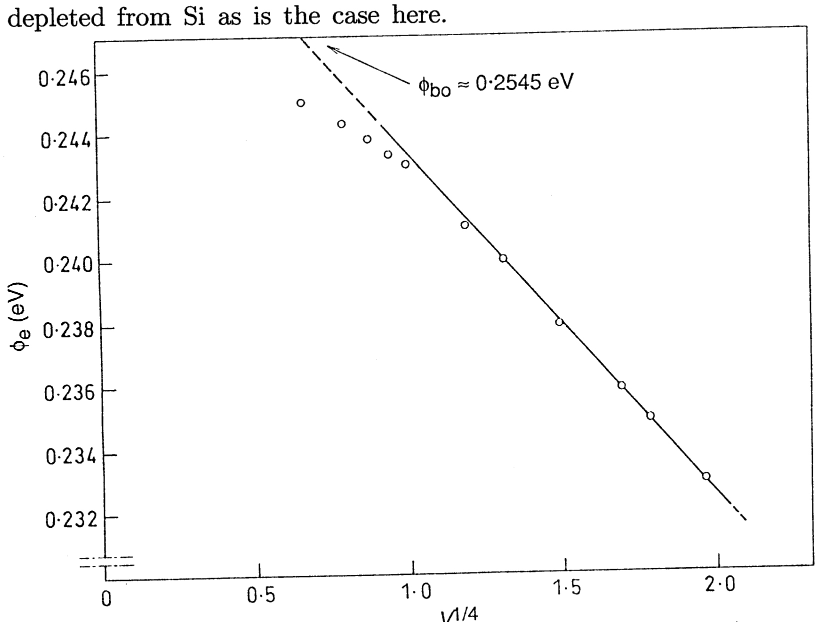

Fig. 2. Plot of the effective barrier height as a function of $V^{1/4}$.

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.

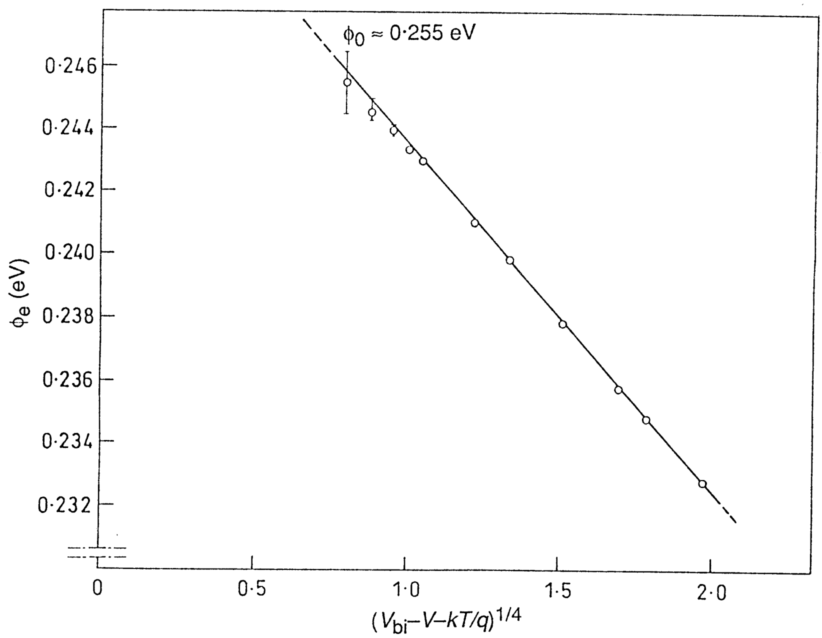

Fig. 3. Plot of the effective barrier height as a function of $(V_{bi}-V-kT/q)^{1/4}$.

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.

References

Chin, V. W. L. (1990). Ph.D. Thesis, University of New South Wales.
Chin, V. W. L., Green, M. A., and Storey, J. W. V. (1991*a*). *Solid-St. Electron.* **34**, 931.
Chin, V. W. L., Newbury, S. M., Theden, U., and Storey, J. W. V. (1991*b*). *Aust. J. Phys.* **44**, 67.
Chin, V. W. L., Storey, J. W. V., and Green, M. A. (1989). *Solid-St. Electron.* **32**, 475.
Chin, V. W. L., Storey, J. W. V., and Green, M. A. (1990). *J. Appl. Phys.* **67**, 4127.
Cohen, J., Vilms, J., and Archer, R. J. (1968). Investigation of semiconductor Schottky barriers for optical detection and cathodic emission. Final Rep. No. AFCRL-68-0651, Contract No. F19628-68-C-0090, Hewlett-Packard Labs, Palo Alto.
Goodman, A. M. (1963). *J. Appl. Phys.* **34**, 329.
Pierret, R. F. (1987). 'Advanced Semiconductor Fundamentals', Vol. 6 (Addison–Wesley: Reading).
Rhoderick, E. H., and Williams, R. H. (1988). 'Metal–Semiconductor Contacts', 2nd edn (Clarendon: Oxford).
Sze, S. M. (1981). 'Physics of Semiconductor Devices', 2nd edn (Wiley: New York).

Manuscript received 17 July, accepted 23 September 1992