CALCULATION OF OPTIMUM IONIZATION ENERGY FOR EXTRINSIC SILICON DETECTORS

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ABSTRACT

Infrared (thermal) imaging is an important area for application of CCD's, because they offer the possibility of incorporating with relative ease a large number of detectors and eliminating or reducing mechanical scanning. In this context extrinsic silicon infrared detectors are of particular interest.

In this paper a theoretical calculation is presented of the performance of extrinsic silicon detectors as a function of cut-off wavelength, ie the dopant ionization energy. We find that for operation in either the 3-5 μm or 8-14 μm bands there is an optimum ionization energy, equivalent to a cut-off wavelength towards the shorter wavelength end of the band. For operation at 77 K, the optimum cut-off wavelength is about 3.6 μm (0.34 eV) for the 3-5 μm band and about 10 μm (0.12 eV) for the 8-14 μm. The calculations suggest that by using a dopant with the optimum cut-off wavelength, other things being equal, a factor can be gained in M* of about 10^4 compared with In for the 3-5 μm band and about 10 compared with Ga for the 8-14 μm band.

1 INTRODUCTION

The advent of CCD's has brought about renewed interest in extrinsic silicon infrared detectors. This is because of all the many possible schemes for combining infrared detectors and CCD's to produce improved thermal imagers, the combination of extrinsic silicon detectors and a silicon CCD seems to offer the best chance of achieving the aim of an imager using a large two-dimensional array of detectors with solid-state readout. For a discussion of the possible different infrared CCD devices and the way in which they might be used see refs 1-3.

There are many possible dopants in silicon which allow detection in one of the two main spectral ranges used for thermal imaging, the 3-5 μm and 8-14 μm bands. The work presented in this paper represents one step in the process of choosing the optimum dopant for operation in either one of these bands. The operation of an extrinsic silicon detector requires the ionization of dopant atoms in the crystal by incident photons, releasing free carriers (electrons or holes) and thereby giving rise to a change in conductivity of the crystal. In this paper we attempt to find what value of ionization energy, other things being equal, gives the optimum detection performance in the wavelength ranges of interest. In reality of course only a limited number of different dopant ionization energies are available, and one cannot expect to find a dopant whose ionization energy is exactly the optimum value, but the results presented here are a useful guide for an initial selection of dopants to be studied. The final choice of dopants will depend on other factors such as the solubility of the dopant in silicon, the magnitude of the photoionization cross section etc.

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An interesting point to emerge from these results is that the impurities which have to date been mentioned most frequently in the literature (refs 4-6) in connection with infrared CCD's, namely In for the 3-5 μm band and Ga for the 8-14 μm band, are far removed from the optimum from the point of view of their ionization energies.

2 DETECTIVITY

We assume that the limiting noise processes in the detector are generation-recombination noise and the fluctuation in the flux of the background photons. The detectivity is then given by the expression (refs 7 and 8):

$$D^* = \frac{\eta\lambda}{hc}\left[\frac{4pd}{\tau} + 2\int_{\lambda_1}^{\lambda_2} \eta F_B \, d\lambda\right]^{-\frac{1}{2}} , \qquad (1)$$

where η is the detector quantum efficiency, λ is the wavelength, p is the hole concentration (to be specific we are considering here an acceptor dopant), d is the detector thickness, τ is the recombination lifetime for holes and $F_B d\lambda$ is the background fluctuation in the wavelength range λ to $\lambda + d\lambda$. The first term in the bracket in Equation (1) corresponds to the generation-recombination noise and the second term is the fluctuation on the background photon flux detected in the range λ_1 to λ_2.

Neglecting multiple reflections the quantum efficiency is given by

$$\eta = (1 - r)(1 - e^{-\sigma N_A^x d}) , \qquad (2)$$

where r is the reflectivity at the front face, σ is the photoionization cross-section (a function of wavelength as discussed in the next Section) and N_A^x is the concentration of neutral acceptors.

The hole concentration is given by

$$p = \tfrac{1}{2}\left[(K^2 + 4KN_A)^{\frac{1}{2}} - K\right] , \qquad (3)$$

where N_A is the total concentration of acceptors (neutral and ionized) and K is the equilibrium constant

$$K = \tfrac{1}{2}\left(\frac{2\pi m_h kT_D}{h^2}\right)^{3/2} \exp\left(\frac{-E_A}{kT_D}\right) \equiv K_o \exp\left(\frac{-E_A}{kT_D}\right) . \qquad (4)$$

where m_h is the effective mass for holes and E_A is the ionization energy for the acceptor.

For detector temperatures T_D likely to be of interest here (well below room temperature) only a small fraction of the centres are thermally ionized, ie $N_A >> p$, and

$$p \cong (KN_A)^{\frac{1}{2}} . \qquad (5)$$

For a p-type semiconductor assuming phonon assisted capture the hole lifetime can be written (ref 9)

$$\tau = \frac{1}{B}\left[p + \frac{(N_D + p)(N_A - N_D)}{(N_A - N_D - p)} \right]^{-1} \quad , \tag{6}$$

where the capture coefficient B is a function of temperature. We assume that at the temperatures of interest the crystal is effectively uncompensated, ie $p >> N_D$. This is an ideal which would not always be achieved, although it should be possible for detectors operated around 77 K. Eq (6) then becomes

$$\tau \cong 1/2Bp \quad , \tag{7}$$

where p is given by Eq (5).

3 PHOTOIONIZATION CROSS-SECTION

In this paper we use two different forms for the photoionization cross-section σ as a function of wavelength. Any function describing σ must be zero for wavelengths greater than $\lambda_E = hc/E_A$, the cut-off wavelength. For fairly deep acceptor centres the profile due to Lucovsky (ref 10) has been shown to be a good approximation, and can be written

$$\sigma_{Luc} = \sigma_o x_E^{\frac{1}{2}} (x - x_E)^{3/2}/x^3 \quad , \tag{8}$$

where $x \equiv hc/\lambda kT_B$ and T_B is the background temperature. σ_o should be approximately constant for a range of similar impurities in a given solid. For the Lucovsky profile the maximum cross-section occurs at a wavelength $\lambda_E/2$ and has a value

$$\sigma_{max} = \sigma_o/8x_E \quad . \tag{9}$$

Some donor centres [eg S/Si, (ref 11)] have maximum cross-sections which occur at wavelengths greater than $\lambda_E/2$ and for these the photoionization profile can be approximately described by a simple rectangular function

$$\begin{aligned} \sigma &= \bar{\sigma} \; ; \quad \lambda \leqslant \lambda_E \\ &= 0 \; ; \quad \lambda > \lambda_E \end{aligned} \tag{10}$$

In the present analysis we want to be able to relate the rectangular and Lucovsky profiles and this may be done as follows: Let

$$\bar{\sigma} = \frac{1}{\lambda_E} \int_0^{\lambda_E} \sigma_{Luc}(\lambda) \, d\lambda \tag{11}$$

$$= \frac{3\pi}{128} \frac{\sigma_o}{x_E} \tag{12}$$

Thus for given values of σ_o and x_E we can form a Lucovsky profile using Eq (8) or a rectangular profile using Eq (12).

4 EXPRESSIONS FOR FIGURE OF MERIT

A useful figure of merit for the performance of a detector in a thermal imaging system is the quantity M* as follows: (ref 12)

$$M^* = \int_0^\infty a(\lambda)\, D^*(\lambda) \left.\frac{\partial W(\lambda)}{\partial T}\right|_{T_B} d\lambda \quad , \tag{13}$$

where $a(\lambda)$ is the atmospheric transmission factor and $W(\lambda)$ is the black body radiation function given by

$$W(\lambda) = \frac{2\pi c^2 h}{\lambda^5} \frac{1}{e^x - 1} \tag{14}$$

For the present calculations we assume an idealized atmospheric transmission with $a(\lambda) = 1$ in the 3-5 μm (or 8-14 μm) band and zero elsewhere.

The mean square fluctuation on the background photon flux falling on the detector in the wavelength range $d\lambda$ is (refs 7 and 8):

$$F_B\, d\lambda = \sin^2\alpha \frac{4\pi c}{\lambda^4} \frac{e^x}{(e^x - 1)^2} d\lambda \tag{15}$$

where α is the half-angle of the cone of the incident background radiation on the detector (eg defined by a cold shield). Substituting Eqs (1), (4), (5), (7), (14) and (15) into Eq (13) we obtain

$$M^* = \frac{\frac{\pi c}{T_B}\left(\frac{kT_B}{hc}\right)^3 \int_{x_2 \text{ or } x_E}^{x_1} \frac{\eta(x) x^3 e^x}{(e^x-1)^2} dx}{\left[2dBN_A K_o \exp\left(-\frac{T_B}{T_D} x_E\right) + 2\pi c \sin^2\alpha \left(\frac{kT}{hc}\right)^3 \int_{x_2 \text{ or } x_E}^{x_1} \frac{\eta(x) x^2 e^x}{(e^x-1)^2} dx\right]^{\frac{1}{2}}} \tag{16}$$

where

$$\eta = (1 - r)\left\{1 - \exp\left[-\sigma_o N_A d \frac{x_E (x - x_E)^{3/2}}{x^3}\right]\right\} \tag{17}$$

for the Lucovsky profile and

$$\eta = (1 - r)\left\{1 - \exp\left[-\frac{3\pi}{128} \frac{\sigma_o}{x_E} N_A d\right]\right\} \tag{18}$$

for the rectangular profile. Note that for the rectangular profile η is not a function of the variable x, so that it may be taken outside the integrals in Eq (16). For the lower limit to the integrals in Eq (16) one chooses the lower value from x_2 or x_E, ie the upper wavelength cut-off is set either by the atmospheric window (x_2) or the activation energy (x_E). The cut-off at x_1 for the fluctuation integral could be achieved by means of a cooled filter.

5 NUMERICAL EVALUATION OF M*

The quantity M* in Eq (16) has been evaluated as a function of x_E and the results are shown in Fig 1 for the 3-5 μm band and Fig 2 for the 8-14 μm band, with M* plotted against the cut-off wavelength $\lambda_E = hc/x_E kT_B$. We now discuss the choice of numerical values used for the evaluation.

According to Soref (ref 13) the capture coefficient B has a $T^{-5/2}$ dependence above T = 10 K and a value ~ 10^{-11} m^3 sec^{-1} at 23 K. Using these values we therefore take

$$B = 2.5 \times 10^{-8} T_D^{-5/2} \quad (m^3 \text{ sec}^{-1}) \quad . \tag{19}$$

For α we choose a value 30°, corresponding to an overall 60° field of view for the detector. For d a value of 100 μm is used; this is to some extent an arbitrary value, although a reasonable one because values much greater than this lead in practice to optical cross-talk between adjacent detectors (ref 6) while values much smaller lead to low values of quantum efficiency. For the total acceptor concentration a value $N_A = 10^{23}$ m^{-3} is used; this is again a somewhat arbitrary value although it is a typical upper limit to what might be achieved with several dopants. The pre-exponential K_o is calculated from Eq (4) with $m_h = 0.58\ m_o$, the value for silicon. For the background and detector temperatures we choose T_B = 300 K and T_D = 77 K; the value of 77 K for the detector is somewhat higher than temperatures discussed in the literature for extrinsic silicon detectors, but it is used here because one of the objects of the present study is to explore the possibility of finding dopants offering useful performance at 77 K.

To obtain a value for the cross-section parameter σ_o we have proceeded as follows: From ref 14 we have $\sigma_{max} \cong 5 \times 10^{-20}$ m^2 for Ga/Si and 1.5×10^{-20} m^2 for In/Si. Using these values in Eq (9) with the appropriate values of x_E we obtain $\sigma_o = 1.1 \times 10^{-18}$ and 7.2×10^{-19} respectively. For the purpose of the present calculations we need a "universal" value of σ_o which is representative of a wide range of dopants, and using the above values as a guide we have chosen $\sigma_o = 10^{-18}$ m^2.

6 CONCLUSIONS

From M* graphs in Figs 1 and 2 the optimum cut-off wavelengths are seen to be about 3.6 μm (corresponding to an ionization energy of 0.34eV) for the 3-5 μm band and 10.0 μm (0.12 eV) for the 8-14 μm band. The cut-off wavelengths for In and Ga are shown on the graphs, and it is clear that both these dopants are far removed from the optimum (for operation of 77 K). Indeed it is seen from the graphs that there is a factor of ~ 10^4 to be gained in the 3-5 μm band and ~ 10 in the 8-14 μm band, as compared with In and Ga respectively. The physical explanation for the occurrence of the maximum in the M* curves is that as the cut-off wavelength is reduced from some high value both the noise and signal (the latter being the black body radiation detected) are reduced, but the

noise decreases more steeply than the signal down as far as the optimum cut-off wavelength.

As already stated, it is unlikely that a dopant can be found with an activation energy exactly equal to the optimum, but it is clearly worthwhile to investigate those dopants having values in the region of the optimum. A discussion of some dopants in this category is given in ref 3, some of the most likely candidates being Mg (11 μm, 0.11 eV) and Te (8.9 μm, 0.14 eV) for the 8-14 μm band and S (6.9 μm, 0.18 eV), Ni (5.4μm, 0.23 eV) and Tl (4.8 μm, 0.26 eV) for the 3-5 μm band. It must be stressed again that having an activation energy close to the optimum does not guarantee that a dopant will produce a good detector, particularly in the context of IRCCD's.

It is also seen from Figs 1 and 2 that the degree of enhancement in going towards the optimum cut-off wavelength is more marked with the rectangular photoionization cross-section profile. Thus we can expect that amongst the n-type dopants, whose photoionization profiles tend to be of a more rectangular nature, it will be relatively even more advantageous to seek one with an activation energy near to the optimum.

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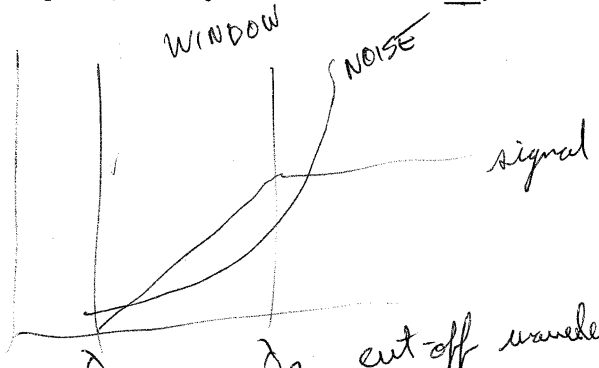

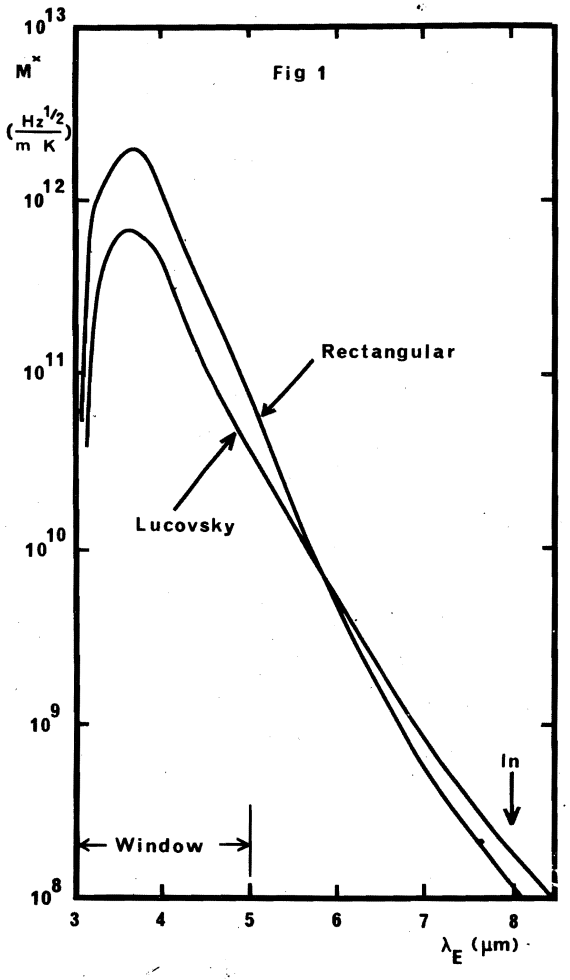
Fig 1
M^*
$(\frac{Hz^{1/2}}{m\ K})$
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
Rectangular
Lucovsky
In
Window
3
4
5
6
7
8
λ_E (μm)

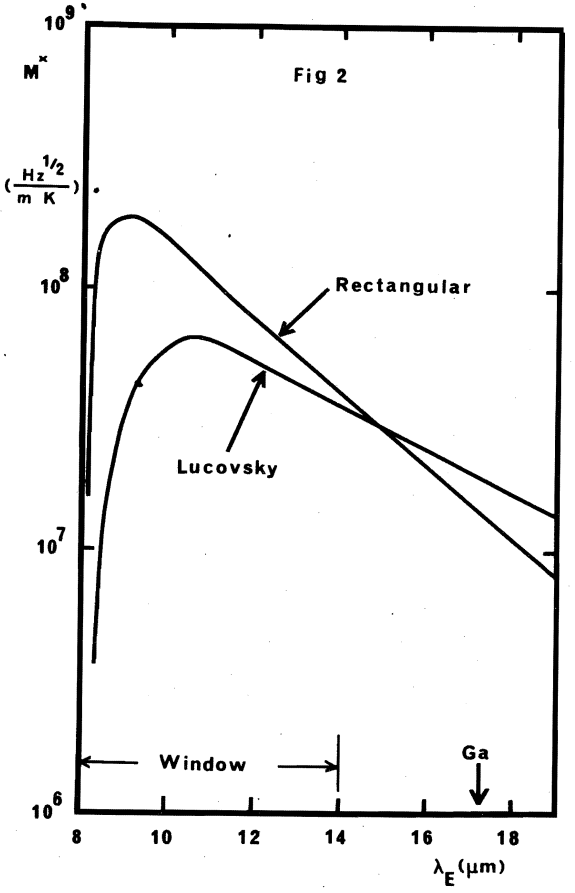
Fig 2
M^*
$(\frac{Hz^{1/2}}{m\ K})$
10^{9}
10^{8}
10^{7}
10^{6}
Rectangular
Lucovsky
Window
Ga
8
10
12
14
16
18
λ_E (μm)