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ABSTRACT

An analysis is presented which permits computation of the required dopant levels, thicknesses and other parameters of an extrinsic silicon infrared photoconductor to ensure that the photogenerated charge output is within the acceptance limits for direct injection into CCDs.

INTRODUCTION

When charge-coupled devices (CCDs) are used to read-out infra-red signals from an extrinsic silicon photoconductive IR detector array, the photo-generated charge from each element may be transferred to the CCD and shifted to the edge of the detector array (direct injection) or may be used to modulate the gate voltage of the CCD (indirect injection). Where direct injection is employed it is important that the magnitude of the photogenerated charge is within the handling capability of the CCD, or, if larger, that some form of background subtraction can be performed prior to injection. The analysis below explores the parameters governing this compatibility for two types of devices. In the first a 100 μm thick photodetector is interfaced with a depletion mode CCD, whilst in the second the infra-red sensitive detector region is diffused or implanted into the surface region above a buried channel CCD. In this configuration the maximum detector thickness would be no more than one micron.

THE PHOTOCONDUCTIVE DETECTOR

For thermal imaging applications detector systems with noise equivalent temperature differential (NEΔT) values of better than 0.1°K are required. NEΔT is a figure of merit for the complete detector/optics combination and is related to the detectivity D* of the detector element by the expression (ref 1)

$$NE\Delta T = \frac{4f^2 B^{\frac{1}{2}}}{aD^*A^{\frac{1}{2}}} \tag{1}$$

in which f is the aperture number of the lens system, B the electrical bandwidth of the detector, a is a constant and A is the area of the element.

For a background photon-noise limited IR detector (ref 2)

$$D^* = \frac{\lambda}{2h_c} \left[\frac{\eta}{\phi_B}\right]^{\frac{1}{2}} \tag{2}$$

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in which λ is the wavelength of incident radiation, h Planck's constant, c the velocity of light, ϕ the background photon flux and η the internal quantum efficiency of the device.

η may be rewritten as

$$\eta \simeq N_T \sigma_{ph} d \tag{3}$$

where N_T is the concentration of photo-ionisable centres, σ_{ph} the photo-ionisation cross-section and d the detector thickness. By substitution of equations (2) and (3) into equation (1) we can define the concentration of photo-ionisable impurity centres required to give $0.1°K$ thermal resolution, as a function of the detector thickness and charge integration time t $(t = \frac{1}{2B})$.

The required expression is

$$N_{T(0.1°K)} = K \cdot \frac{1}{td} \tag{4}$$

where

$$K = 32 \times 10^2 \cdot \frac{h^2 c^2}{a^2 \lambda^2} \cdot \frac{\phi_B}{\sigma_{ph} A}$$

Figure 1 shows this relationship for detectors of various thicknesses.

CHARGE HANDLING CAPABILITY OF THE CCD

The dynamic range of the CCD can be defined in terms of input photo-generated charge N by the expression

$$\frac{N_{Noise}}{c} \leqslant N \leqslant N_{max} \cdot S \tag{5}$$

which simply requires that the injected charge should exceed the product of the CCD self noise N_{Noise} and the inverse of the scene contrast ratio c, whilst remaining below the charge-saturation limit of the CCD defined by the product of N_{max} and CCD electrode area S.

For a depletion mode CCD N_{max} is approximately 10^{12} electrons cm^{-2} and N_{Noise} is about 700 electrons (ref 2). One of the fundamental problems of IR imaging is the low scene contrast ratio c, (0.004 for $0.1°K$ resolution) which considerably increases the lower limit of acceptable charge injection. Substituting the above values in equation (4) and assuming a CCD channel length of 10 μm and width of 25 μm gives

$$1.75 \times 10^5 \leqslant N \leqslant 2.5 \times 10^6 \text{ electrons} \tag{6}$$

The photogenerated charge input to the CCD is given by the expression

$$N = \eta \phi_B A t G \tag{7}$$

where η is the quantum efficiency, ϕ_B the background photon flux, A the detector area, t the integration time and G the photoconductive gain.

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Since $\quad \eta = N_T \sigma_{ph} d$ $\hspace{6cm}$ (8)

and $\quad G = \dfrac{V\mu\tau}{d^2}$ $\hspace{6.5cm}$ (9)

where V is the applied voltage, μ the carrier mobility and τ the carrier lifetime.

Substitution of equations (7), (8) and (9) into equation (6), assuming that

$$\phi_B = 2.7 \times 10^{15} \text{ photons cm}^{-2} \text{ sec}^{-1} \quad \text{(f/1 FOV)}$$
$$\mu = 10^4 \text{ cm volt}^{-1} \text{ sec}^{-1}$$
$$\tau = 10^{-8} \text{ sec}$$
$$\sigma_{ph} = 10^{-16} \text{ cm}^2$$
$$A = 2.5 \times 10^{-5} \text{ cm}^2$$

gives:

$$2.6 \times 10^{14} \leqslant \frac{N_T V t}{d} \leqslant 3.7 \times 10^{15} \hspace{3cm} (10)$$

Thus values of $N_{T_{min}}$ and $N_{T_{max}}$ can be obtained.

It is now possible, by comparing equations (4) and (10), to examine the range of acceptable deep level centre concentrations, N_T, as a function of integration time, detector thickness or photoconductive gain. Figure 2 shows the N_T range as a function of integration time for a 100 μm thick photoconductor with a photoconductive gain of unity.

A similar analysis may be performed for buried channel CCDs; in this case the maximum absorption depth d will be about 1.0 μm. Using a limiting noise value of 200 electrons and a well capacity of 10^{11} electrons cm^{-2} (ref 2) gives

$$3.7 \times 10^{13} \leqslant \frac{N_T V t}{d} \leqslant 3.7 \times 10^{14} \hspace{3cm} (11)$$

The relationship between deep level centre concentration N_T and integration time in buried channel devices is given in figure 3.

Figure 4 shows the effect on this comparison of varying the photoconductive gain. Where photoconductive gain is present a minimum practical limit is defined by the requirement that the generation recombination noise should exceed the Johnson noise in the detector circuit. This limit is indicated by the broken vertical line in figure 4.

The corresponding case for a buried-channel CCD is shown in fig 5, the chosen integration time being 4×10^{-2} seconds and the absorption depth d, 1 μm.

DISCUSSION

Using equation 4 and figure 1 it is possible to examine the trade-offs between integration time, deep-level centre concentration and detector thickness in achieving 0.1°K temperature resolution. In general the

maximum solid solubility of deep impurities in silicon lies between 10^{16} and 10^{18} cm^{-3}. Assuming 10% electrical activity defines a maximum upper N_T concentration limit of 10^{17} cm^{-3}, which places a minimum detector thickness of about 100 μm on high bandwidth systems (t = 4 x 10^{-4} secs), but still permits the choice of detectors approximately one micron thick for large-area staring arrays (t = 4 x 10^{-2} secs). The upper limit on detector thickness is governed by the on-set of optical cross talk between adjacent elements. Nummedal et al (ref 3) have recently shown that for 50 x 25 x 500 μm detectors a cross talk value of 11% is expected. Accordingly the above analysis has been restricted to detectors less than 200 μm thick.

From figure 2 it is seen that the output from a 100 μm thick detector is well-matched to a depletion mode CCD, the N_T (0.1°K NEΔT) curve lying mid-way between the charge acceptance limits of the CCD. In contrast, figure 3 indicates that the use of a one micron thick detector in conjunction with a buried-channel CCD would require reduction of the IR detector charge output prior to insertion into the CCD. This is a direct consequence of the reduced dynamic range of the buried-channel CCD with respect to the depletion mode CCD.

In the absence of photoconductive gain the curves for CCD and IR detector bear the same relationship to one another irrespective of detector thickness – only the absolute value of the required N_T concentration changes. If, however, photoconductive gain is present, equations (4) and (10) show an opposite dependence on gain and it is therefore possible, in principle at least, to correct for the mismatch between detector and CCD by adjustment of detector gain, as shown in figure 4. In each case there is a minimum limit to the acceptable gain in order to ensure that generation-recombination noise, rather than Johnson noise remains the dominant noise mechanism. This limit, together with the minimum deep-level centre concentration limit for 0.1°K resolution and $N_{T_{max}}$ and $N_{T_{min}}$ defines the compatibility range, the shaded area in figure 4. For compatibility between the 100 μm thick IR detector operating at unity photoconductive gain the N_T concentration must lie between 3 x 10^{14} and 9.5 x 10^{14} cm^{-3}, the former being the optimum value. Decreasing the gain to 2 x 10^{-1} broadens the acceptable N_T range to cover values from 3 x 10^{14} to 4.5 x 10^{15}, with an optimum concentration of 10^{15} cm^{-2}. These values are for a full staring array (eg 10^5 picture points, 25 Hz frame time).

Although the use of photoconductive gain permits additional flexibility in tailoring the IR detector to suit the depletion mode CCD, care must be exercised in its use, particularly in large-area staring arrays, since variations in gain from element to element will lead to increases in fixed-pattern noise. Note also that, as indicated in fig 5, fractional gain cannot be used to reduce the unacceptably high charge injection level for a buried-channel CCD, since this would involve operation in a Johnson noise limited mode.

CONCLUSIONS

The charge output from an extrinsic silicon IR photoconductor element of typical dimensions and doping level is well-matched to depletion mode CCDs for direct injection purposes. For use with buried-channel devices some form of background subtraction must be provided prior to injection.

ACKNOWLEDGEMENTS

REFERENCES

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LIST OF FIGURES

10^{19}

10^{18}

10^{17}

(cm^{-3})

10^{16}

N_T (0.1°K)

10^{15}

10^{14}

10^{13}

BLOCK SCANNED

STARING ARRAY

d (cm.)

10^{-4}

10^{-3}

10^{-2}

10^{-1}

10^{-4} 10^{-3} 10^{-2} 10^{-1}

Integration Time t (sec.)

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