Modulation-transfer-function-enhanced readout for SPRITE detectors

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A new readout structure is investigated for signal-processing-in-the-element detectors that yields a modulation transfer function that is 3.5 dB better than those currently used. Experimental verification is performed in Si rather than HgCdTe, with similarity relations derived for the two semiconductors.

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1. Introduction

The basic principle of a signal-processing-in-the-element (SPRITE) detector is the utilization of the drift of carriers to perform a time-delay-and-integration function.[1] This process produces a charge image that is sensed in a readout structure. The readout structure used in SPRITE detectors plays an important role in determining the signal fidelity of the detector. The two most common readouts have a square shape and a tapered shape, as shown in Fig. 1.[2] The resistance of the readout is changed by the charge passing through it, which causes a corresponding change in voltage developed across the readout when the SPRITE is driven by a constant current source.

Because the signal voltage is developed across a finite distance, the output voltage is a local average of the charge image intensity. Because of this spatial averaging, the readout imposes a limit on the resolution of the detector,[3] with the horn readout having a slightly better modulation transfer function (MTF). We have investigated a resistive-type readout structure and found that it has a substantially better MTF (3.5 dB) than the voltage-type readouts.

The experimental investigation of new readout structures has been hampered by the fact that all SPRITE detectors are made from HgCdTe. A convenient substitute material is Si, which can be used to

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design demonstration devices. When the scaling relations developed in Section 2 are used, these Si devices produce experimental results that are directly comparable with the results that would be obtained from a similar structure made from HgCdTe. Several readout designs that we fabricated in Si are explored in Section 3, and their impulse responses and MTF's are compared.

2. Similarity Relations between Si and HgCdTe

Similarity relations connect the design parameters of the experimental structure to those of the actual detector. When the principles of dimensional analysis are used,[4] the model detector must have the same dimensionless numbers as the actual device. For SPRITE detectors there are seven dimensionless numbers involved: three spreading numbers, N_{sx}, N_{sy}, N_{sz}; the drift number, N_{dz}; and three boundary numbers, N_{bx}, N_{by}, and N_{bz}.[5]

Suppose that we have two materials, A and B, each with unique mobility μ, diffusivity D, and carrier lifetime τ. If the drift numbers in both devices are set equal, the resulting relation between the operating voltages of the two devices, U_A and U_B, is

$$\frac{U_A}{U_B} = \frac{\mu_B D_A}{\mu_A D_B}.$$ (1)

We must also relate the physical device dimensions. If we denote the length, width, and depth of the two devices as l_A, l_B, w_A, w_B, d_A, and d_B, geometrical similarity implies that

$$\frac{l_A}{l_B} = \frac{w_A}{w_B} = \frac{d_A}{d_B}.$$ (2)

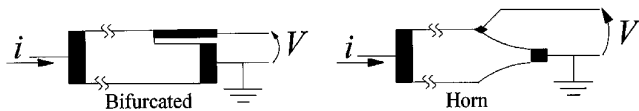To determine the physical dimension relations com-

Fig. 1. Two common SPRITE readout structures. A direct current is applied to the bias contact, and the readout voltage is measured from the ground to the readout contacts. The along-scan length of the readout is usually set equal to the cross-scan width of the SPRITE. A typical width in HgCdTe is 63 µm. i, bias current; V, measured voltage.
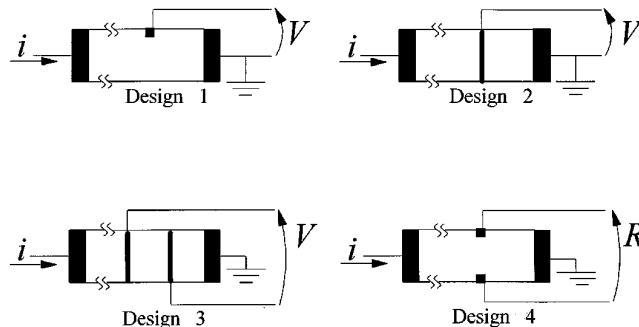

Fig. 2. Readout structures implemented in Si. A direct bias current is applied, and voltage or resistance is measured across the terminals as indicated. In each case the along-scan length of the readout and the cross-scan width of the SPRITE are both 4 mm. R, measured resistance.

pletely, the ratio of the lengths of the two devices, l_A and l_B, must be written. We can do this by equating the length spreading numbers:

$$\frac{l_A}{l_B} = \frac{(D_A \tau_A)^{1/2}}{(D_B \tau_B)^{1/2}} . \tag{3}$$

The three remaining dimensionless numbers, the boundary numbers, determine the surface velocities. This relationship for surface velocities in the two materials, V_{SA}, V_{SB}, is

$$\frac{V_{SA}}{V_{SB}} = \frac{(D_A \tau_B)^{1/2}}{(D_B \tau_A)^{1/2}} . \tag{4}$$

With similarity relations, Eqs. (1)–(4), silicon can be used to mimic the behavior of HgCdTe. The diffusion length for Si is 66 times longer than that of HgCdTe,[6,7] and so the Si device is 66 times larger in each dimension. The operating voltage for Si SPRITE's is 3.9 times larger than HgCdTe. A typical long-wave IR SPRITE in HgCdTe has dimensions of 750 µm × 63 µm × 10 µm and operates at ~2-V bias. The corresponding Si SPRITE has dimensions of 50 mm × 4.1 mm × 0.66 mm and operates at 7.8 V. These specifications are easily accommodated in the laboratory, and Si SPRITE readouts were fabricated with standard lithographic techniques.

3. Experimental Results

Four different readout structures were fabricated in Si according to similarity relations, Eqs. (1)–(4). They are shown schematically in Fig. 2. For voltage-type readouts (designs 1–3) the voltage signal across the readout is measured at the high-impedance input of an oscilloscope while a constant current was applied to the bias terminal of the device.

Design 1 is a point-contact readout, similar in form to the currently used bifurcated readout, and thus serves as a reference design. The output voltage is measured from the ground bias contact to the read electrode, which makes contact with the Si through a small square hole in the passivating oxide. Design 2 is a single-line-contact readout. The sensing electrode makes contact with the Si through a wide rectangular window in the oxide. Design 3 is a two-line-contact readout, each contact with the same dimensions as in design 2. The intent here is to provide a second readout terminal for sensing the

voltage changes. Because very little negligible current flows through both sensing leads, less contact noise should be present, and this should yield improved noise performance.

Design 4 is a two-point resistive readout. While a constant current is applied to the bias terminal, an ac sensing voltage is applied across the readout terminals. The resulting ac is measured with a current sensitive synchronous detector with a bandwidth large enough to pass all the signals of interest (50 kHz for Si, 2.5 MHz for HgCdTe). The frequency of the ac voltage is high enough (100 kHz for Si and 5 MHz for HgCdTe) that it does not affect the charge motion and to be significantly higher than any signal frequencies.

The impulse response of the readouts was measured with an impulse input created by a Nd:YAG laser scanned by a rotating polygon mirror. By scanning a spot of light over the readout, the signal measured at the output of the detector is the impulse response of the SPRITE readout. This is Fourier transformed and divided by the Fourier transform of the input spot irradiance profile (a square-shaped pulse 2 mm wide) to yield the readout MTF. The observed noise level of all the readouts was approximately equal.

The impulse responses for each of these detectors are plotted in Fig. 3. Readouts 1–3 all have impulse responses of similar width, which results from the
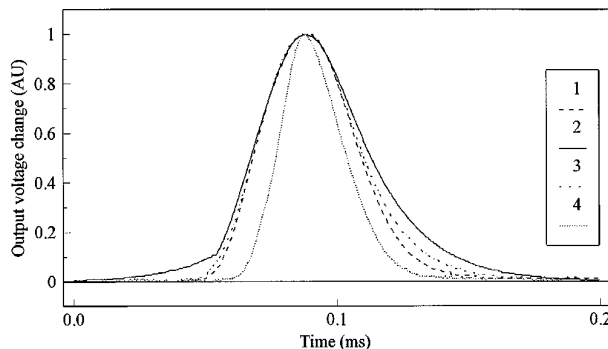

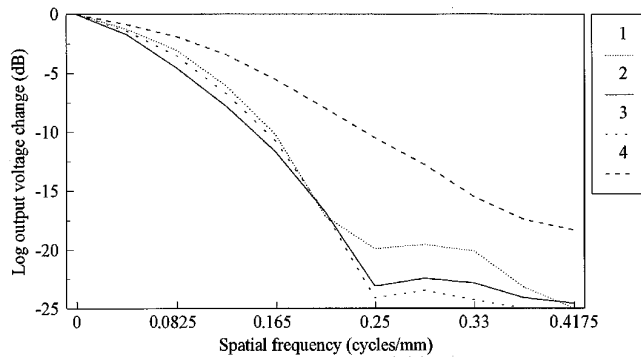Fig. 3. Impulse responses of the four Si readouts tested.

Fig. 4. MTF's of the four Si readouts tested.

fact that they all have the same averaging region length of 4 mm. The impulse response of readout 1 is slightly narrower than 2 and 3 because only one end boundary of the readout is defined by a line contact. Readout 4 produces a markedly narrower impulse response. This is because the two sensing electrodes are in the cross-scan direction rather than the along-scan direction, resulting in a shorter averaging region.

The readout MTF's are seen in Fig. 4. Readouts 2 and 3 have a distinct minimum at one cycle per readout length (=0.25 cycles/mm), caused by their well-defined rectangular geometry. Readout 1 has a less well-defined minimum at 1 cycle/readout. Readout 4 has no distinct minimum because of its point-contact nature, and it has a higher MTF

overall. At 0.125 cycles/mm, which corresponds to 0.5 cycles/readout, design 4 has an MTF that is 3.5 dB higher than all the other readout types tested.

4. Conclusions

Several SPRITE readout designs were fabricated and tested in Si. A new type of two-point resistive readout was demonstrated to have a MTF that is 3.5 dB better at midband frequency.

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