Abstract—A compressing photodetector structure suitable for detecting continuous wave and long pulswidth optical signals is described for applications such as acousto-optical signal processing and machine vision. Subthreshold injection of carriers over a photodetector blooming gate is used to generate a compressing transfer characteristic. The photodetector transfer characteristic is integrating at low light levels and logarithmic compressing at higher light levels. The output voltage at which logarithmic compression becomes dominant may be adjusted in a range extending below 5 nW incident optical power by varying the bias voltage difference between the photodetector blooming and imaging gates. The predictions of simulated models that were developed correlate well with the experimental measurements.

I. INTRODUCTION

The dynamic range requirements of optical processing applications such as machine vision and acousto-optical (AO) spectrum analysis cannot be met with conventional integrating photodetector arrays [1]–[14]. To meet these dynamic range requirements—which may be as high as 80 dB (10^10) in optical power, with the maximum useful optical power being as low as 300 µW or less—photodetector circuits with a compressing transfer characteristic are usually required [3], [5]. A compressing transfer function reduces the effective quantization noise at low optical power levels for a given analog-to-digital (A/D) converter resolution. The amount of compression required at the detector is a function of the system requirements, including the resolution of the A/D converters [3], [5]. For example, in some applications the resolution of the A/D converter is limited to 8 bits. The ratio of the maximum useful output voltage to the minimum useful output voltage then is limited to 256 to 1. A logarithmic transfer function is desirable for many applications [3], [5], [12], [13].

The photodetector structure described below is intended for use with long pulswidth optical waveforms. For these waveforms the compressing photodetector structure reaches steady-state operation during the interrogation period. This photodetector structure, however, generally is not suitable for AO signal processing applications requiring short (≈100 ns) optical pulse detection.

In short optical pulse applications the photogenerated charge can leak from the imaging region before the end of the interrogation period, making it difficult to determine the amplitude of the pulse. Thus, for short optical pulse applications, it is generally necessary that the compressing photodetector either contain or be followed by a peak detector [3], [5]. The photodetector structure presented in this paper thus can be useful for AO communications applications [5], some AO radar spectrum analysis applications [5], and machine vision.

The device structure, device theory, and experimental results are described below. The photodetector structure contains a blooming gate, imaging gate, and transfer gate and is compatible with a charge coupled device (CCD) readout multiplexer [15].

II. COMPRESSING PHOTODETECTOR PRINCIPLES

Fig. 1 shows a cross section, schematic, and electric potential profile of the subthreshold-conduction-compressing photodetector. This photodetector is similar to conventional CCD imagers [15] except that the blooming gate is biased with a small potential offset between the blooming and imaging gates. The device principles and structure are described below.

During operation, photogenerated carriers are initially integrated under the imaging gate (Fig. 1). At higher photocurrent levels, however, the photocarriers are injected from the imaging gate region over the blooming gate potential barrier into the drain, resulting in a slowing of the rate of photocarrier accumulation with increasing photocurrent. The slowing of the rate of carrier buildup with increasing photocurrent results in a compressive transfer characteristic. The mechanism of photocarrier injection over the blooming gate potential barrier (Fig. 1) is similar to subthreshold conduction in a metal-oxide-semiconductor-field-effect transistor [16], [17]. It is shown below that in the subthreshold-conduction region of operation the number of photocarriers accumulated in the imaging gate region increases logarithmically with increasing optical power. At the end of the interrogation period, the photocarriers accumulated in the imaging gate region are transferred to a floating diode sensor readout circuit (Fig. 1). In a conventional CCD the accumulated charge would be transferred to a CCD multiplexer register.

The transfer characteristic for this subthreshold operation is well described by a relationship similar to (15) in [1]. The appropriate expression for the total number of
carriers, \( N_T \), in the imaging gate region for the subthresh-
hold operation is

\[
N_T = \frac{nCV_T}{q} \ln \left( \frac{I_L + I_p}{I_L + I_p \exp \left( -\frac{(I_L + I_p)\phi_t}{nCV_T} \right)} \right)
\]

where \( k \), \( T \), \( q \), \( n \), \( C \), \( V_T \), \( I_L \), \( I_p \), and \( \phi_t \) are the Boltzmann constant, the absolute temperature, the electronic charge, the subthreshold parameter [16], the capacitance of the storage region, the thermal voltage \((kT/q = 0.026 \text{ V})\) at room temperature, the leakage current, the photocurrent, and the interrogation period, respectively. The leakage current \((I_L)\) is the effective subthreshold current flowing from the imaging gate region to the drain (Fig. 1) under the selected dc conditions with no light incident on the detector.

Fig. 2 shows the calculated transfer functions \((N_T\) as a function of \(I_p\)) obtained from (1) for several interrogation period values with \(I_L\) and \(n\) taken to be 1 \(\mu\)A and 1, respectively. The first portion of each of the curves, at low photocurrent levels, corresponds to integration of the photocurrent. At higher photocurrent levels, the logarithmic compression of the photocurrent occurs because of the subthreshold conduction of carriers over the blooming gate potential barrier to the drain (Fig. 1). The current level at which the transition from integration to compression occurs depends strongly on the interrogation period. This relationship can be qualitatively understood by examining the time constant, \( \tau \), when subthreshold conduction becomes dominant. This time constant is given by (18) in [1] as

\[
\tau = \frac{CV_T}{I_L + I_p}.
\]

For most operating conditions, the photocurrent is much larger than the leakage current. Thus, \( \tau \) is inversely pro-
portional to the photocurrent. For short interrogation periods, \( \tau \) must be short if subthreshold conduction and thus compression are to become dominant during the interrogation period; consequently, the photocurrent must be large (2), and thus the integration portion of the transfer characteristic that occurs before compression becomes dominant is large. For long interrogation periods, however, subthreshold conduction and thus compression may become dominant during the interrogation period for long values of \( \tau \); in this case, the photocurrent is small (2), and thus the integration portion of the transfer characteristic that occurs before compression becomes dominant is small.

### III. Photodetector Structure, Results, and Analysis

Fig. 1 shows a schematic of the compressing photodetector structure and readout circuit used to test the operation of the compressing photodetector. The photodetector was illuminated by the light spot from an HP8150A programmable light source (850 nm wavelength) having an optical-fiber pigtail. The light from the fiber was first collimated and then focused to a \(1/e^2\) spot size of 15 \(\mu\)m. At the end of an interrogation period, the transfer gate was enabled, and a standard reset floating diode readout circuit was used to sense the amount of charge transferred from the imaging gate region (Fig. 1).

The charge accumulation area beneath the imaging gate (Fig. 1) is defined by a conventional localized-oxide-structure field oxide in one lateral direction and by the blooming and transfer gates (that is, by the distance between them) in the orthogonal lateral direction (horizontal direction in Fig. 1). These dimensions are 13 and 20 \(\mu\)m, respectively. The imaging gate is formed in the second polysilicon layer that overlaps both the transfer and blooming gates by 2 \(\mu\)m thus having a total length of 24 \(\mu\)m (horizontal direction in Fig. 1). Both the transfer and blooming gates are formed in the first polysilicon layer. The length of both the transfer and blooming gates is
8 μm (horizontal direction in Fig. 1). The length of the opening in the light shield is 16 μm (horizontal direction in Fig. 1). The devices were fabricated using a commercial n-buried channel CCD process.

Fig. 3 shows a typical photodetector output at a high photocurrent level. The signal of interest is the difference between the output level just before and after the transfer pulse. This difference corresponds to the amount of charge transferred from the imaging gate region to the floating diode sensor. The large baseline slope observed at high photocurrent levels (Fig. 3) is due to the diffusion of minority photocarriers, created deep in the substrate, directly to the floating diode sensor.

Fig. 4 shows the measured voltage output due to charge transferred to the floating diode sensor as a function of input optical power for different blooming gate bias ($V_B$) values and a fixed interrogation period, $t_I$, of 200 μs. The transfer characteristics for less negative blooming gate bias values are predominantly logarithmic with relatively small integration portions at low optical power levels. The transfer characteristics for the most negative blooming gate bias values, however, show large photocurrent integration regions at low optical power levels.

The rapid rise in the detector output voltage at the higher optical power levels is thought to result primarily from the transport of photocurrent directly from the imaging gate region to the floating diode sensor during the time the transfer gate is on. The bottom curve in Fig. 4 gives evidence for this point; it shows the simulated output voltage change due only to charge transferred to the floating diode sensor during the 300 ns transfer pulse. This increase in the detector output voltage at the higher optical power levels can be minimized by decreasing the transfer gate pulsewidth (transfer time), $t_T$, as shown by the measured data in Fig. 5.

The transfer function of the compressing detector has a strong dependence on the difference between the electric potential in the imaging gate region, $\phi_I(I_L)$, and the electric potential in the blooming gate region, $\phi_B$. This difference in electric potential, $\Delta \phi_{IB}$, is the barrier height (Fig. 1). The barrier height is a function of the dark leakage current, $I_L$, and is given by

$$\Delta \phi_{IB} = \phi_I(I_L) - \phi_B. \quad (3)$$

The relationship of the electric potential in the imaging gate region, $\phi_I(I_L)$, to the dark leakage current ($I_L$) is [1]

$$\phi_I(I_L) = -V_T \ln \left( \frac{I_L}{I_{LD}} \right) + \phi_0 \quad (4)$$

where $\phi_0$ and $I_{LD}$ are the dark electric potential in the imaging gate region and the dark subthreshold current, respectively, under dc conditions chosen such that the subthreshold current may be considered not appreciable ($\approx 10^{-14}$ A, for example). The barrier height thus is

$$\Delta \phi_{IB} = -V_T \ln \left( \frac{I_L}{I_{LD}} \right) + \phi_0 - \phi_B. \quad (5)$$

Thus, the barrier height is dependent on the negative of the logarithm of $I_L$ or, equivalently, on the logarithm of the inverse of $I_L$. From (2) and (5), the time constant and barrier height, respectively, are small for a large $I_L$ value; thus, for a fixed interrogation period ($t_I$), the integration
portion of the transfer characteristic that occurs before compression becomes dominant is small. However, from (2) and (5), the time constant and barrier height, respectively, are large for a small $I_L$ value; for a fixed interrogation period in this case, the integration portion of the transfer characteristic that occurs before compression becomes dominant is large.

In fitting the simulated transfer function from (1) with the experimental data, it was assumed that $I_{io}$, corresponding to a barrier height of

$$\Delta \phi_{ib} = \phi_{ib} - \phi_{p},$$

was $2 \times 10^{-14}$ A. The transfer characteristic for this leakage current value was calculated using (1). Then experimental transfer characteristics for different values of $V_B$ were compared to this simulated curve to determine the blooming gate bias, $V_{B0}$, that gave the best fit. The subthreshold parameter, $n$, was then found as follows. First, (1) was used to determine the value of $I_L$, here called $I_{1L}$, for the given experimental value of $V_B$ used in obtaining the experimental transfer characteristic (Fig. 4); this value of $V_B$ is here called $V_{B1}$. Second, $n$ was determined from the expression

$$I_{1L} = I_{io} \exp \left[ \frac{-q(V_{B1} - V_{B0})}{nkT} \right].$$

Modifications of (1) were made to fit the experimental data shown in Fig. 4. One modification was including the charge integrated during the short transfer pulse by adding the second term in (8) below. This gave

$$N_T = \frac{nCV_T}{q} \ln \left( \frac{I_L + I_P}{I_L + I_P} \exp \left[ \frac{-(U_L + I_P)T}{nCV_T} \right] \right) + \frac{I_P T}{q}.$$  

(8)

For a large barrier height, $\Delta \phi_{ib}$, (1) was further modified to include an initial integration of the photocurrent

$$N_T = \frac{I_P T}{q}$$

(9a)

to a subthreshold level given by $N_T \leq C(V_B - V_{B0})/q$ and then a subthreshold conduction mode of operation given by

$$N_T = \frac{C \Delta \phi_{ib}}{q} + \frac{nCV_T}{q} \ln \left( \frac{I_L + I_P}{I_L + I_P} \exp \left[ \frac{-(U_L + I_P)T}{nCV_T} \right] \right) + \frac{I_P T}{q}.$$  

(9b)

for $N_T > C(V_B - V_{B0})/q$. Equation (8) is appropriate for a small imaging gate to blooming gate electric potential difference corresponding to a predominantly logarithmic transfer characteristic (subthreshold conduction dominant). Equations (9a) and (9b) are appropriate for a large imaging gate to blooming gate electric potential difference corresponding to a transfer characteristic with a large photocurrent integration region at low optical power levels.

The calculated transfer characteristics were fit to the experimental data using a detector quantum efficiency of 10%, an imaging region storage capacitance of 95 fF, and a floating diode sensor responsivity of 0.5 μV per electron. The top experimental curve in Fig. 4, corresponding to a blooming gate bias of $-4.1$ V, was fit using (9a) and (9b). This curve corresponds to conventional CCD imager operation with a large imaging gate to blooming gate electric potential difference. The middle two curves in Fig. 4 for blooming gate biases of $-3.5$ and $-3.2$ V were fit using (8). As shown in Fig. 4, a good fit to the experimental data was obtained over the range of optical power measured. The subthreshold parameter value, $n$, used to fit the data was 1.25. The transfer gate pulse length used in the calculations was 300 ns. As noted above, the bottom curve in Fig. 4 is the calculated output for charge transfer to the floating diode sensor resulting only from photocarriers generated during a 300 ns transfer pulse.

The performance of these compressing photodetectors is improved over earlier work using the subthreshold conduction effect [1], [8], [10], [11]. The integration portion of the transfer characteristic is smaller relative to the compressive portion. In addition, the photodetectors are completely reset thus minimizing delay and eliminating kTC reset noise. Since the potential barrier does not depend on the drain bias, higher uniformity across an array may be obtainable. The performance of the compressing photodetectors reported here can be further improved by reducing the direct minority carrier diffusion to the floating diode sensor (Fig. 3). This minority carrier diffusion in the substrate to the readout circuit is the primary potential difficulty in using these compressing detector approaches. Improved crosstalk isolation, using a number of transfer gates between the compressing detector region and the readout, and keeping the gates of receiving wells in accumulation until just prior to the transfer pulse, may provide improved performance. Other methods, such as using a backside p-n junction [3], [5] or vertical overflow drain structure, can also enhance crosstalk isolation. The estimated dynamic range is ≥ 60 dB (10^6) in optical power if the detector noise level, quantum efficiency, $I_T$, and maximum incident optical power are assumed to be 100 electrons, 10%, 200 μs, and 2 μW, respectively.

IV. CONCLUSIONS

A compressing photodetector structure that utilizes the subthreshold operation of carrier injection over the blooming gate to generate a compressing transfer characteristic required in applications such as AO spectrum analysis is described. This subthreshold conduction compressing photodetector is optimum for long interrogation times (20–200 μs). It exhibits a primarily logarithmic compressing characteristic and has an estimated dynamic range of ≥ 60 dB (10^6) for a maximum optical signal power of 2 μW. Excellent agreement was obtained between device simulations and experimental measurements for this subthreshold conduction detector. The device
should be useful for communications, some radar spectrum analysis, and machine vision applications.

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REFERENCES

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