LOW LIGHT LEVEL PERFORMANCE OF A CHARGE-COUPLED AREA IMAGING DEVICE

Rudolph H. Dyck and Michael D. Jack

ABSTRACT

A 100 x 100 element charge-coupled imaging device[1] has been characterized for its low light level performance below room temperature and at a frame rate near the television standard. It is an n-channel device of the buried-channel, two-phase implanted barrier type. Good imaging performance was obtained at temperatures from 30°C down to -60°C. At room temperature the useful dynamic range was limited by dark current non-uniformities to approximately 100:1. Near -40°C the dynamic range was better than 1000:1 and was limited on the low end by noise from the on-chip preamplifier.

A major reason for interest in the operating characteristics of this type of device below room temperature is the possibility of increasing the useful dynamic range by virtue of reduced dark current and dark current non-uniformity. Also of special interest in charge-coupled imaging devices is the charge transfer efficiency at the desired operating temperature and over the dynamic range of the device.

At -60°C the dark current and dark current non-uniformity were not detectable in the normal mode of operation. Charge transfer efficiency, which was in excess of 0.9999 at high signal levels, was investigated at low signal levels by measuring the linearity of response to a light spot illuminating a single photoelement in the device in the absence of any other illumination. Linearity of response was found, on most units tested, to be preserved down to the preamplifier limited uncertainty level of ± 300 electrons.

INTRODUCTION

With the conception of the buried-channel charge-coupled imaging device,[1] there came the possibility of a large area solid-state imaging device with orders of magnitude higher light sensitivity than had previously been suggested for such a device. It then appeared possible to transfer arbitrarily small amounts of charge without substantial loss, and to sense these small amounts of charge with a detector element of exceptionally low capacitance. This paper reports on the low light level performance of one of the first CCD area image sensors of the buried-channel type, a 100 x 100 photoelement image sensor.[2]

---

(1) L. Walsh and R. H. Dyck, "A New Charge-Coupled Area Imaging Device", presented to the CCD Applications Conf., San Diego, CA., Sept., 1973. See also Fairchild CCD 201 Data Sheet.

(2) L. Walsh and R. H. Dyck, Fairchild Semiconductor, CCD 201 Data Sheet.

Research and Development Laboratory, Fairchild Camera and Instrument Corporation, 4001 Miranda Ave., Palo Alto, Ca. 94304.

Near room temperature dark current effects are in general the major limitation to sensitivity. With cooling, these dark current effects are substantially reduced to the point where one of the following effects limit sensitivity: preamplifier noise, low charge transfer efficiency or non-uniformities caused by structural defects.

DESCRIPTION OF THE 100 x 100 ELEMENT IMAGE SENSOR AND ITS PERFORMANCE AT ROOM TEMPERATURE

A schematic diagram of the device is shown in Fig. 1. This type of functional device organization is achieved with the use of one opaque, vertical register for each column of sensor elements. Illumination is from the front side. Except for the opaque stripes which prevent light from falling directly onto the vertical registers, all the area is light sensitive. Polysilicon layers are used to form all three gate structures which give transmittance for wavelengths greater than approximately 450 nm. The amplifier is a differential gated charge integrator. It provides a saturated signal output of approximately 75 mV and a drive impedance of approximately 500 ohms.

The register possesses a two-phase electrode system with undoped polysilicon between the doped polysilicon electrodes. Barriers are ion implanted in such a way that the trailing edge of each barrier, i.e., the edge, away from the output contact, is self-aligned to the trailing edge of each electrode. This is the structure for the barrier between each sensor element and its corresponding vertical register channel as well as the barriers within the vertical and horizontal registers.

At room temperature, high quality imaging has been demonstrated with this device at 30 frames per second over a dynamic range of approximately 20:1. A video image is shown in Fig. 2; the dynamic range at the display output is estimated to be approximately 20:1. Highlights in the picture are close to the saturation level of the device. At reduced image intensities and with appropriate gain adjustments, the image quality remains high with the exception that dark signal non-uniformities become apparent. Fig. 3 shows a picture for the case of a highlight signal level equal to 10 percent of saturation. In this picture the small white spots are the dark signal effects; the vertical streaks are attributed to structural imperfections that degrade charge transfer efficiency in a few of the vertical registers. At still lower image intensities the picture quality is finally limited by the random noise sources in the device and the associated amplifier circuits. In this investigation the dominant noise source is capacitance noise in the differential gated charge integrator. The total noise results in a device dynamic range of approximately 400:1 when other effects such as dark current non-uniformities are disregarded.

THE EFFECTS OF TEMPERATURE ON DARK-SIGNAL-LIMITED PERFORMANCE

It has been observed in a variety of buried-channel charge-coupled devices that both the average dark signal and the dark signal non-uniformities have a temperature dependence which is approximately the same as the intrinsic carrier concentration parameter, n_i, for silicon over the temperature range from 25°C to approximately -10°C; it is smaller below -10°C. Fig. 4 shows the temperature dependence of dark signal for a representative 100 x 100 element device. This figure also shows a calculated curve based on a measured room-temperature dark current density of 2 nA/cm^2 and the temperature dependence of the parameter n_i.

The calculated average, peak-to-peak and rms dark signal levels are plotted as a function of temperature in Fig. 5. An average dark current density proportional to n_i and equal to 10 nA/cm^2 at 25°C is assumed. This current density generates a dark charge of ∿ 2% of saturation for a 24 msec integration period, which was typical for the units studied. At room temperature the peak-to-peak dark signal is approximately 10% of saturation maximum. This limits the dynamic range at a small number of points. In principle, only the shot noise from a perfectly uniform background dark signal limits the dynamic range at low signals; in practice, a background dark level causes an offset which saturates further stages of amplification, when signal levels less than an order of magnitude smaller than the background dark current are to be amplified. As seen in Fig. 5, the dark current shot noise is negligible below room temperature. Below -40°C all dark current "noise" is below the rms amplifier noise.

CHARGE TRANSFER EFFICIENCY AT LOW SIGNAL LEVELS

At temperatures below -40°C, amplifier noise and charge transfer inefficiency become the dominant limitations to device performance at low signal levels. Amplifier noise can be reduced by suitable signal processing. A drastic fall-off of transfer efficiency with signal-level, however, would be a fundamental limitation to low light level imaging.

Transfer efficiency was determined for several arrays by measuring the response of the array to a light spot imaged onto a photoelement. Since transfer efficiency is, in general, a function of signal level for these devices, the conventional technique of determining it from the amplitude of the first trailing charge packet normalized to the amplitude of the leading charge packet leads to erroneous results for low signal levels. A more reliable method developed for this study is to measure the linearity of response to decreasing light-spot intensity for a photoelement remote from the amplifier. A nonlinear decrease in output pulse amplitude for lower light intensity represents a charge loss in the array. This method is limited only by the accuracy of calibration of light attenuating neutral density filters and the linearity of the output amplifier.

Linearity of response is clearly indicated in Fig. 6 which shows the response of an array to a light spot, expressed in electrons plotted against the input illumination level, expressed in electrons. The unit was operated at -50°C at a frame rate of 40 Hz and a bit rate of 500 KHz.

The light spot was located at the photosensor in the 96th column and the 97th row. Thus, charge introduced by the light undergoes approximately 200 transfers along the vertical register and 200 transfers along the horizontal register. The data points follow a straight line to within experimental error from illumination levels ranging from 50% of saturation to 0.2% of saturation. This indicates that no large reduction in transfer efficiency occurs at signal levels approaching the noise level of the amplifier.

IMAGING AT LOW LIGHT LEVELS

A series of photographs taken at illumination levels successively reduced from the near-saturation level with neutral density filters is shown in Fig. 7. The device was operated at -40°C to minimize dark-current effects. The input light level was determined at the near-saturation level by measuring the current in the reset drain circuit of the amplifier. The average input light level for the image in Fig. 7(a) was 120,000 electrons/pixel. The highlight level determined by substitution of a blank image was 360,000 electrons/pixel. Input levels for reduced illumination were determined from the neutral density filter calibration.

A discernible image is obtained at an average signal level of 120 electrons/pixel (a highlight level of 360 electrons/pixel), as may be seen in Figs. 7(d) and 7(f). The single frame image in Fig. 7(d) shows the salt-and-pepper type of noise from the amplifier. Signal-to-noise enhancement is obtained when this noise is averaged over many cycles by taking a long exposure photograph as may be seen in Fig. 7(f). The figure also emphasizes that it is this amplifier noise that limits the dynamic range of the device.

CONCLUSION

Imaging over a range of illumination of 1000:1 has been demonstrated with a 100 x 100 photoelement buried-channel CCD imaging device. A discernible image, which averaged 120 electrons/pixel (360 electrons/pixel highlight), was obtained. The transfer efficiency of cooled units in the absence of dark current or bias charge has been shown to remain high at signal levels approaching the rms noise level of the on-chip amplifier.

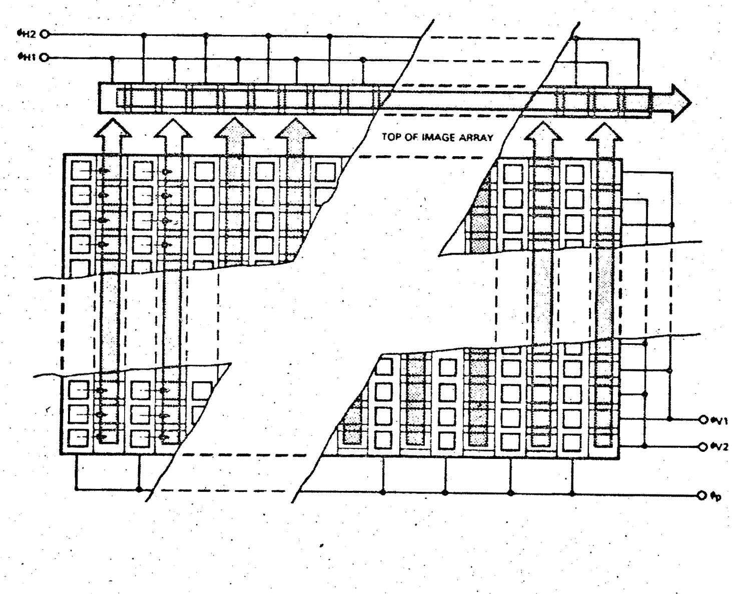


FIG. 1 SCHEMATIC DIAGRAM OF THE 100 x 100 ELEMENT AREA IMAGING DEVICE

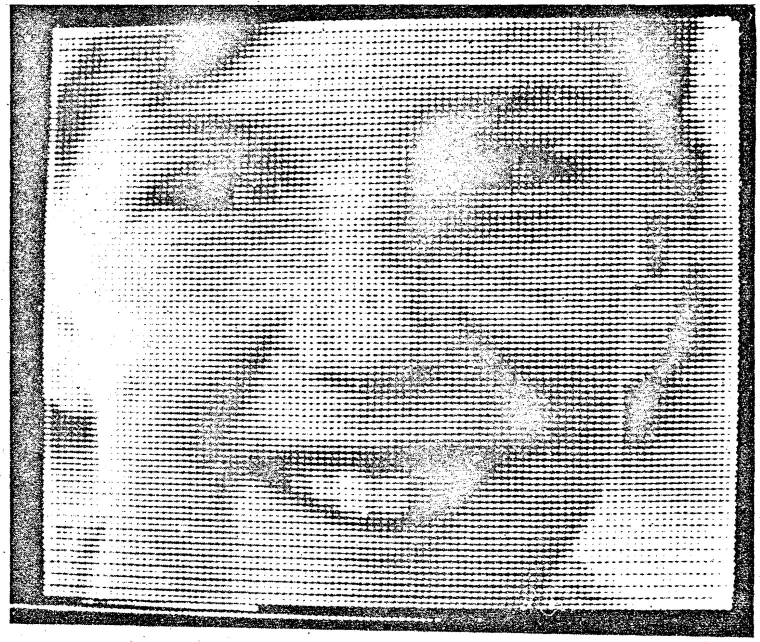


FIG. 2 IMAGING AT 27^{o}C NEAR SATURATION ILLUMINATION LEVEL.

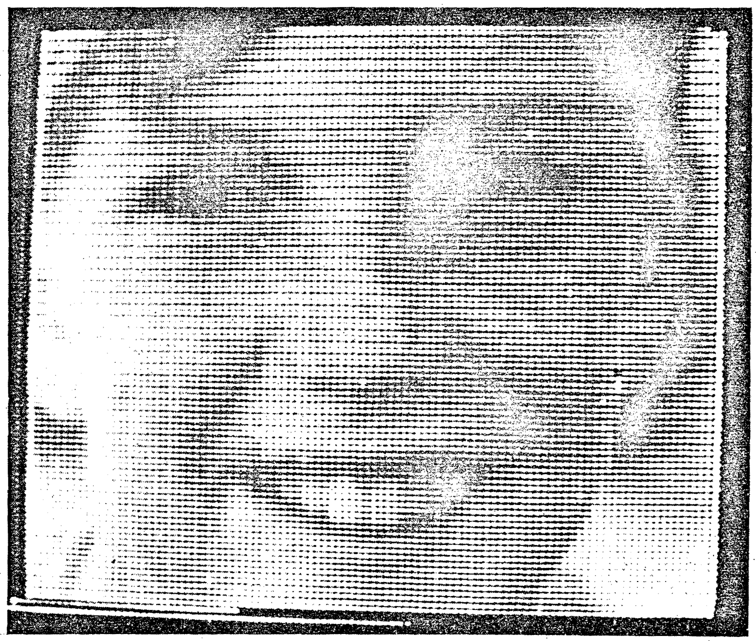


FIG. 3 IMAGING AT 27^{o}C AT 10% OF SATURATION ILLUMINATION LEVEL.

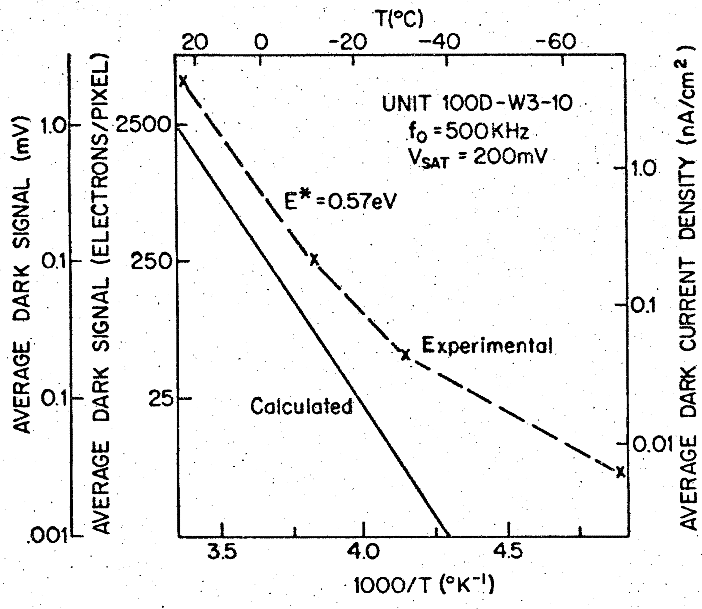


FIG. 4 EXPERIMENTAL AND CALCULATED CURVES OF DARK CURRENT VS. TEMPERATURE. THE EXPERIMENTAL DATA WAS TAKEN WITH A UNIT EXHIBITING AN AVERAGE DARK CURRENT OF 2 nA/cm^2 AT ROOM TEMPERATURE. THE TWO ORDINATES ON THE LEFT GIVE THE DARK OUTPUT AND THE CORRESPONDING DARK CHARGE PER PIXEL. THE ORDINATE ON THE RIGHT GIVES THE CALCULATED DARK CURRENT DENSITY.

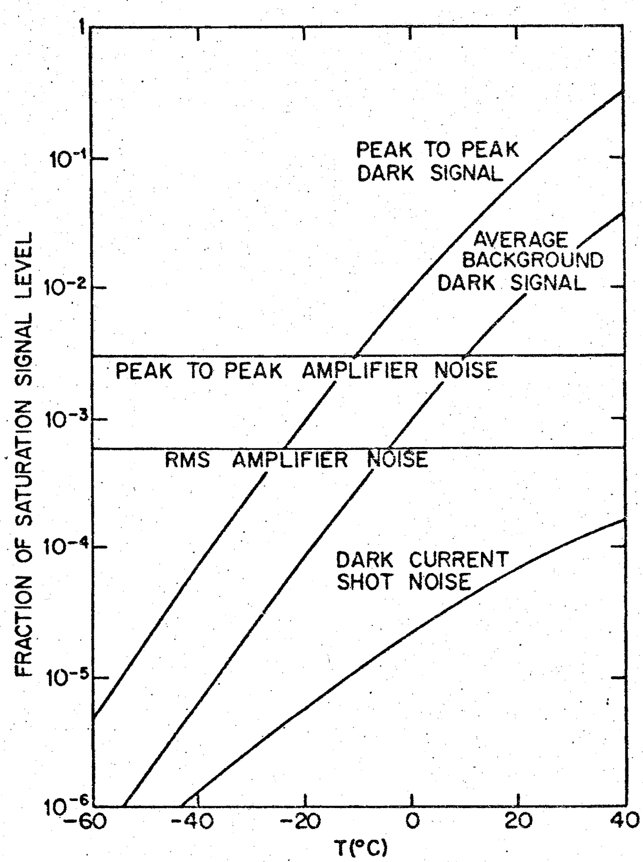


FIG. 5 PEAK-TO-PEAK, AVERAGE AND RMS DARK SIGNAL PLOTTED AGAINST TEMPERATURE, EXPRESSED AS A FRACTION OF SATURATION. ALL CURVES ARE CALCULATED FOR $J_D \approx 10nA/cm^2$ FOR ROOM TEMPERATURE.

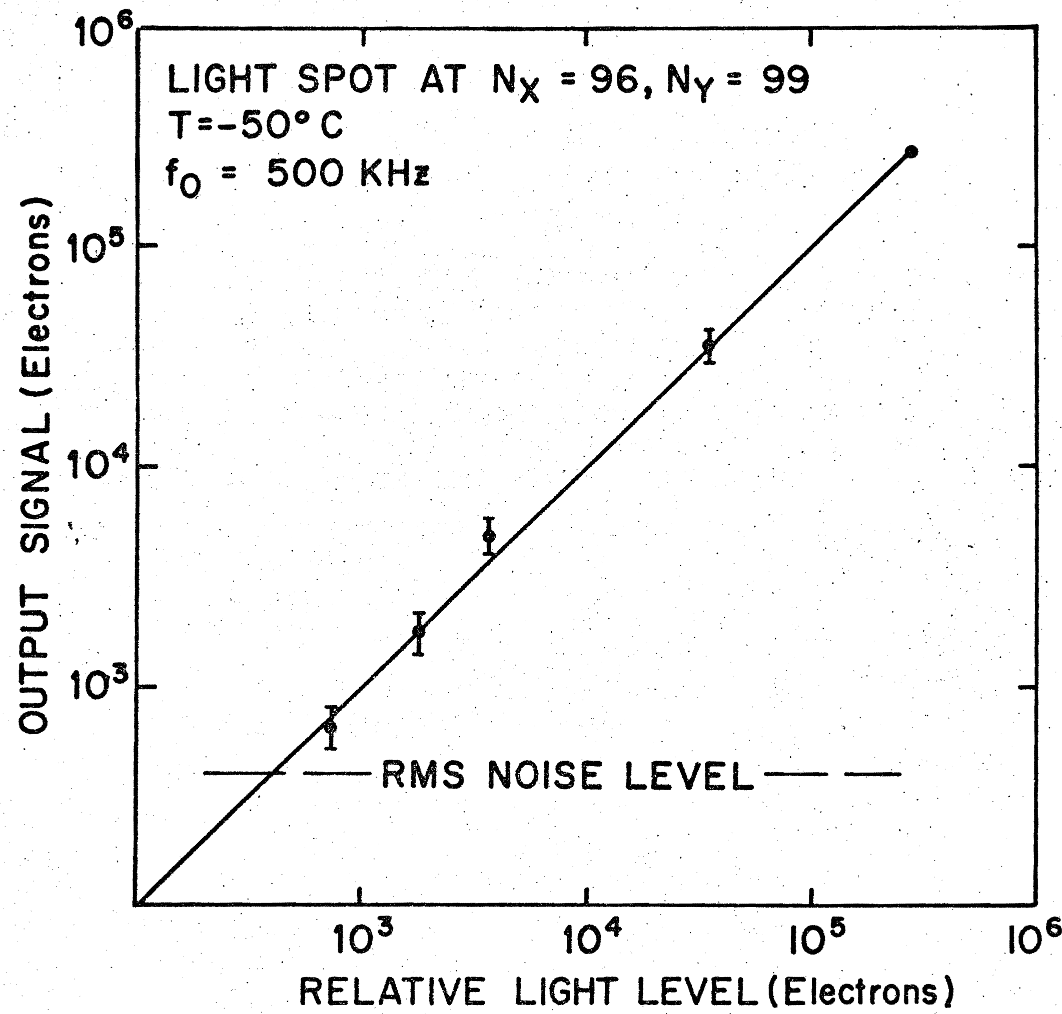
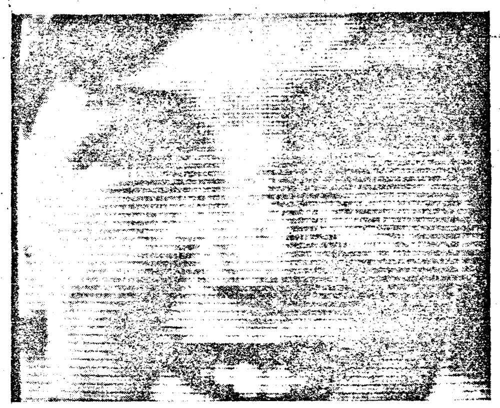


FIG. 6 OUTPUT SIGNAL VERSUS RELATIVE LIGHT LEVEL IN ELECTRONS.

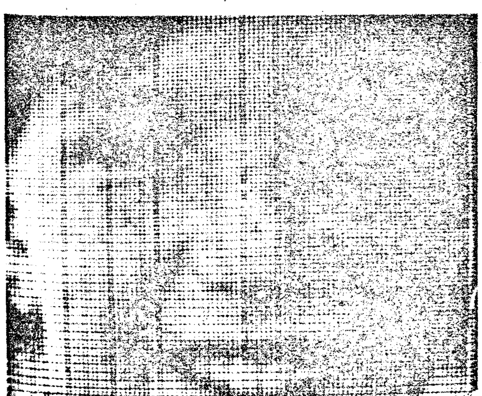
(a) Average Signal Level
≃120,000 Electrons/Pixel
1/30 sec. Exposure



(b) Average Signal Level
≃12,000 Electrons/Pixel
1/30 sec. Exposure

(c) Average Signal Level
≃1200 Electrons/Pixel
1/30 sec. Exposure

(d) Average Signal Level
≃120 Electrons/Pixel
1/30 sec. Exposure



(e) Average Signal Level
≃1200 Electrons/Pixel
5 sec. Exposure

(f) Average Signal Level
≃120 Electrons/Pixel
10 sec. Exposure

FIG. 7 IMAGING AT -40°C. ILLUMINATION LEVEL WAS SUCCESSIVELY ATTENUATED BY A FACTOR OF TEN IN FIGURES (a) TO (d). FIGURES (e) AND (f) WERE MADE AT THE SAME ILLUMINATION LEVELS AS FIGURES (c) AND (d), RESPECTIVELY.