

CCD Imager Development for Astronomy

Barry E. Burke, James A. Gregory, Michael Cooper, Andrew H. Loomis, Douglas J. Young, Thomas A. Lind, Peter Doherty, Peter Daniels, Deborah J. Landers, Joseph Ciampi, Kay F. Johnson, and Peter W. O'Brien

Charge-coupled-device (CCD) technology has played a major role over the past two decades in various Lincoln Laboratory applications involving space surveillance. The important performance metrics for those programs include high quantum efficiency, low-noise readout circuits, and large pixel counts. The Advanced Imaging Technology Group has developed over a period of many years a leading-edge capability in all these areas. The same detector features that are important to space surveillance are likewise eagerly sought by astronomers, and for the past twelve years we have been engaged in various programs to make our CCD technology available to several observatories. These programs have had a reciprocal benefit to us by supporting development of novel device concepts and supplying us with comprehensive test data that we otherwise would not have the resources to obtain. This article reviews our work in imager development for astronomy, with special emphasis on a new CCD architecture called the orthogonal transfer array. This device will be featured in a gigapixel focal-plane array now in assembly for the first of four telescopes in a wide-field survey observatory called Pan-STARRS.

HARGE-COUPLED DEVICES, OF CCDs, are well known in consumer products such as digital cameras and camcorders. Because of cost constraints, however, these products do not come close to delivering the achievable performance of the technology. With special chip designs and wafer processing a CCD can be an order of magnitude more sensitive and have a spectral response that extends out to the limits of silicon cutoff at about 1.1 μ m, well beyond the approximately 700 nm cutoff of consumer cameras. In addition, the chip sizes and pixel counts can, with current wafer fabrication technology, far exceed the fingernail-size devices commonly available. These high-performance versions of CCDs, developed here at Lincoln Laboratory and at other laboratories, are a vital component in diverse military surveillance and scientific applications.

Research in CCD technology at Lincoln Laboratory goes back to the mid-1970s, when the first experi-

mental devices were designed and fabricated under an Air Force-funded program called GEODSS (Groundbased Electro-Optical Deep-Space Surveillance). The GEODSS program was led by the Aerospace Division and involved development of a space surveillance capability using state-of-the-art optical sensors on wide-field ground-based telescopes. The most sensitive image sensors of that era were based on vacuum-tube technology. It was clear at that time that a solid-state device such as the CCD had the potential to overcome many of the limitations of the tube-based imagers, including their low quantum efficiency, limited spectral response, limited size, and finite lifetime. By the late 1980s and early 1990s we had supplied several high-performance CCDs for surveillance programs, including the Space-Based Visible [1] and LINEAR programs [2].

The astronomy community was also an early adopter of CCDs, beginning in the 1970s with the first commercially available devices. Astronomers foresaw then that the CCD, with its electronic readout, high dynamic range, and high quantum efficiency, would doom the photographic plate (the mainstay detector technology for nearly a century) to oblivion. The detector features desired for space surveillance turned out to be essentially the same as those desired by astronomers, namely, large-area devices with high quantum efficiency and low noise. It was no surprise, then, that astronomers approached us beginning in 1994 with inquiries about the possibility of making our technology available for their applications.

This article describes two examples of our collaborations with this community. The first, which began in 1994, has led to over a hundred CCDs installed in several observatories around the world, while the second and more recent example involves a novel device architecture for a program called Pan-STARRS that is currently under development. In both cases these programs were mutually beneficial to both parties, with astronomers gaining access to Lincoln Laboratory technology and in return supporting device innovations (some described here) and providing in-depth device characterization.

Sensor Requirements for Astronomy

It is helpful to quantify the usefulness of the various factors that contribute to the productivity of an observatory. The rate at which a telescope can detect objects of a given brightness with a given signal-to-noise ratio is a highly useful and commonly used figure of merit M. This metric depends on the effective collecting area A, the field of view on the sky Ω , the overall system throughput ε , which includes detector sensitivity and duty cycle, and the image quality $\Delta\theta$, which is the detected resolution, or "sharpness," of point sources. For stars and unresolved objects that are more or less uniformly distributed on the sky, this rate is

$$M = \frac{A\Omega\varepsilon}{\Delta\theta^2}.$$
 (1)

Increases in M can be achieved by building larger primary mirrors (A) but at great expense. The other factors in this equation, particularly ε and $\Delta\theta$, have been and can be further improved with advances in detector technology.

For existing observatories with relatively large focal ratios, improvements in Ω call for larger focal-plane arrays of detectors to capture the very wide usable areas available at the telescope focus. This has driven the astronomy community to ask for the largest manufacturable devices, and then to make these devices closely abutting to enable large tiled arrays of sensors. It is also possible to increase Ω by resorting to fast optical

10.0 megapixels



FIGURE 1. Historical timeline showing the development of increasingly larger charge-coupled device (CCD) imagers. The quarter is shown for size comparison.

designs, but this gives rise to a variety of other problems such as complexity of the optics, shallower depth of focus, and smaller sensor pixels. The latter two factors pose challenges to the detector technology. Shallow depth of focus means greater attention to sensor flatness, and smaller pixels lead to greater pixel-to-pixel crosstalk, hence degraded resolution.

The system throughput ε and its implications for CCD technology have received a great deal of attention in recent years. Included in this parameter is the device quantum efficiency, which is the ratio of detected photoelectrons to incident photons. The read noise is also implicitly included in this parameter because it determines the speed with which the collected imagery can be read off the focal plane. Since read noise increases with read rate, as is described later, there is a penalty in trying to increase image readout rates. We can avoid this trade-off by resorting to multiple output ports on the CCD but at the expense of additional complexity in the drive electronics and video output circuitry.

The parameter $\Delta \theta$ is determined by optical wavefront distortion from atmospheric winds and turbulence, with sites at the highest altitudes providing generally the smallest $\Delta \theta$. As described later, improvements in $\Delta \theta$ have been accomplished only by using adaptive optics, a generally expensive approach that is effective only over a narrow field of view. The orthogonal transfer CCD (OTCCD), which we discuss later, can provide partial electronic compensation for wavefront distortions and improve $\Delta \theta$, at much lower expense.

Lincoln Laboratory CCD Imager Technology Base

In this section we describe the principal features of the CCD technology that are critical to the sponsors we serve. Although the basic fabrication techniques are common to industrial integrated-circuit processing, we have had to develop unique processes and designs to achieve the maximum performance possible. The sidebar "A Primer on Charge-Coupled Devices" (page 370) gives additional detail about the structure of CCDs and their underlying technology.

Large-Scale Devices

The progress in Lincoln Laboratory CCD imager size can be clearly seen in Figure 1, which shows photographs of the different devices made for the GEODSS and other space surveillance programs over nearly two decades. The trend toward larger devices primarily re-



FIGURE 2. Illustration in cross section of (a) a conventional front-illuminated CCD imager, and (b) a back-illuminated CCD imager.

flects a long-term investment by the Laboratory in improvements in our wafer fabrication facilities. The rapid improvements in integrated-circuit technology coupled with continued upgrades in equipment and processing expertise here at the Laboratory enabled us to increase CCD chip areas from less than 0.5 cm^2 in 1975 to a 50 cm^2 device in 1994, the largest in the world at that time. Some of the highlights of these early devices include the 353 kilopixel device first fabricated in 1987, which was used in the CCD focal plane for the Space-Based Visible experiment on the MSX satellite. The 2.1 megapixel imager from 1992 and the 10 megapixel device from 1994 are currently used in ground-based surveillance systems by researchers in the Aerospace division at the Laboratory. These imagers have also been used by the LINEAR program, and have helped place Lincoln Laboratory at the forefront of new asteroid and comet discoveries.

Quantum Efficiency

The second important metric for astronomical detectors is high quantum efficiency, that is, the efficient conver-

A PRIMER ON CHARGE-COUPLED DEVICES

CCCDs, are based on metaloxide semiconductor (MOS) technology. After the invention of the CCD in 1969 at Bell Laboratories, the device underwent rapid development for a variety of applications in electronic imaging, signal processing, and digital memory. However, its principal legacy has been in electronic imaging.

The fundamental element of a CCD is the MOS capacitor, comprising a semiconductor (silicon) substrate, an overlying oxide or other dielectric film, and a conductive gate. The oxide is usually SiO₂, sometimes in combination with other materials, with a thickness ranging from about 0.004 to 0.05 μ m. For comparison, the thickness of this page is 100 μ m. The gate is almost always a deposited film of polycrystalline silicon, or polysilicon as it is usually known, with thicknesses on the order of 0.02 to 0.04 μ m.

Semiconductors have two types of mobile carriers-electrons and holes. In contrast to negatively charged electrons, holes are positively charged. A semiconductor can be made to have predominantly electrons as the current carrying species by adding minute amounts of so-called donors (typically phosphorus or arsenic) to the material. This process, called *doping*, is termed *n* type. By adding boron (a so-called acceptor) to the pure semiconductor, the predominant carrier species becomes holes, and the material is said to be *p* type.

When an MOS capacitor is made on p-type material and the gate is biased positive, the holes are repulsed from the gate area by the resulting fields. A zone depleted of holes (termed a depletion layer) is created and is depicted by the lighter shading in Figure A(1). At the same time, this bias creates conditions favorable for the accumulation of electrons at silicon



FIGURE A. (1) Cross section of a metal-oxide semiconductor (MOS) capacitor consisting of a biased gate electrode, an oxide layer, and a *p*-type silicon substrate. With the gate biased positive, a packet of electrons can be collected and held at the silicon/oxide interface. (2) With two closely spaced MOS capacitors, a packet of electrons can be exchanged between them by using a sequence of voltage steps on the two gates.

surface. In an image sensor these electrons are generated by absorbed light, as illustrated in Figure A(2), but also will appear spontaneously as a result of thermal processes, leading to what we call dark current, or dark charge. Cooling the sensor suppresses this thermal generation, which is an important consideration in low-light-level applications. Exposure times for astronomical imaging may run as much as an hour or more, and the temperatures needed to suppress dark charge to an electron/hour or so are often below -100° C.

The conceptual breakthrough that led to the CCD was the realization that a packet of electrons held under a gate could be shifted to an adjacent MOS capacitor by a proper sequence of voltages applied to the two gates, as illustrated in Figure A(2). Here the voltage on the first capacitor gate is reduced while that on the second gate is raised. The transfer process is not perfect, however, and some electrons may be left behind, usually because of defects called traps that ensnare electrons temporarily. The metric applied to this process is charge-transfer inefficiency (CTI), which is the fraction of the charge packet left behind at each transfer. To minimize this problem, CCDs are almost always made with a thin *n*-doped layer at the silicon surface called a buried channel, as depicted in Figure 5(a) in the main article. Electrons reside within this



FIGURE B. Three-phase CCD showing the silicon substrate, doped layers comprising the buried channel and channel stops, gate and channel-stop dielectric layers, and the polysilicon gates.

layer and avoid the silicon/SiO₂ interface, where large numbers of traps called surface states reside. As a result of careful processing, buried-channel CCDs made here at the Laboratory often achieve CTI values as low as 10^{-7} to 10^{-8} . Such nearly perfect transfer is essential for the very large devices that involve tens of thousands of charge transfers.

Figure B shows a more detailed depiction of a CCD. This example illustrates a three-phase device in which three gates are needed to contain and transfer charge. At any given time, two of them may exchange charge, as illustrated in Figure A(2), while the third is held at a low potential to isolate the charge from neighboring pixels during the transfer. Note also that the gates overlap each other. Since the three gate levels are fabricated in three separate polysilicon deposition and lithographic definition steps, the overlaps (typically about 1 μ m) are

needed to accommodate misalignment and etching tolerances.

Another important feature of the CCD is a so-called channel stop, which defines the edges of the pixel perpendicular to the charge-transfer direction. Typically, a channel stop consists of a region of thicker oxide as well as extra ptype dopant in the silicon. The channel stops and three gates then comprise a pixel. A photograph of one corner of a three-phase imager is shown in Figure C. The distinct color differences between polysilicon gates are the result of optical interference effects in the SiO₂ layers on top of the gates. Also visible in this photo are narrow channel stops running vertically and aluminum bus lines connecting to the gates of each phase.

To read out the array of charge packets, a serial readout register is added at the bottom of the device, as shown in Figure 14. The charge array is shifted down by one row, during which time the bottom row of charge is transferred into the serial register. The serial register then transfers the charge to the sense amplifier. This cycle is then repeated until the imager is cleared.



FIGURE C. The corner of a three-phase CCD imager, showing the narrow vertical channel stops, the three polysilicon gate levels, and the aluminum clock busses.

• BURKE ET AL. CCD Imager Development for Astronomy



FIGURE 3. Processing steps in the fabrication of back-illuminated CCDs.

sion of photons into the photoelectrons that are collected by the CCD for readout. In conventional CCDs for consumer and industrial applications the device is illuminated on the top or circuit side, as illustrated in Figure 2(a). This approach leads to serious loss of photons, either to absorption in the overlying circuit structures or to reflection. To avoid this problem, we have developed a process in which the CCD wafer is chemically thinned to about 50 to 75 μ m thickness and illuminated on the etched or back surface, as illustrated in Figure 2(b). Such devices are called *back illuminated* and can achieve near unity quantum efficiency.

Figure 3 describes the process in more detail. First, a CCD wafer is epoxied face down onto a second wafer, which will become the mechanical support or handle wafer for the thin CCD. Next, most of the approximately 675 μ m of the CCD wafer is removed by a precision chemical etching step until the desired final thickness of the device is reached. The etched surface must then be treated to minimize loss of photoelectrons due to surface defects. Typically, this treatment involves introducing a thin dopant layer at the surface to repel photoelectrons. An antireflection coating is then applied to minimize reflection losses, which would otherwise be substantial because of the relatively high refractive index of silicon (~3.6). A second etch step, called the street etch, is performed to remove the remaining silicon from the perimeter of the device and to gain access to the metal input/output pads on the device.

Figure 4 shows data for front-illuminated and backilluminated CCDs made with this process. Front-illuminated CCDs are essentially blind in the ultraviolet because of strong absorption in the polysilicon CCD gates. In the visible, these gates begin to be moderately transparent, and the quantum efficiency rises to a peak of about 40%. Beyond 800 nm silicon becomes progressively more transparent and thus less able to absorb photons. For consumer CCDs the overall quantum efficiency is even lower than the black curve because color filters are placed over the pixels. For example, a "blue" pixel will have a filter that transmits blue but absorbs the green and red, effectively throwing away two-thirds of the visible photons. In addition, the nature of the CCD processing for these applications eliminates most of the sensitivity beyond 700 nm.

For back-illuminated devices the entire spectrum out to 1000 nm can be usefully detected with high efficiency. In practice, the optimum quantum efficiency needs to be tailored by the choice of antireflection coatings. The red curve in Figure 4 is for a two-layer coating of SiO₂ and HfO₂ designed for visible and near-infrared wavelengths with a transmission peak around 850 nm.



FIGURE 4. Quantum efficiencies of front-illuminated CCDs with back-illuminated CCDs optimized for short and long wavelengths.

This coating has been the most used of all, and is particularly attractive for direct sky imaging and for use on the red arm of spectrographs. For spectroscopy applications in the blue and ultraviolet we use a single layer of HfO_2 ; a typical quantum efficiency curve for this case is shown in blue in the figure.

Noise

The main source of noise in most imaging applications is the so-called photon shot noise, which is due to the random arrival and detection of photons. However, the circuit at the output of a CCD, which converts charge packets into a voltage, contributes to the overall noise on the signal and sets the noise floor for the device. Since almost all the applications for our CCDs emphasize the ability to sense faint objects and targets, the noise set by the charge-sensing circuit is critical to the user. Figure 5 shows three representations of this circuit—the equivalent circuit, a plan view of the device layout, and a photo of a fabricated circuit.

The charge detection process begins when the reset transistor is pulsed on briefly (for a few nanoseconds) to pre-charge a floating n^+ region or sense node to the reset voltage V_{RD} . Then a charge packet of N electrons is transferred onto the floating n^+ node. Associated with this node is a capacitance C. The charge qN, where qis the electron charge, induces a voltage change $\Delta V =$ qN/C on this node. This voltage drop is detected by the sense field-effect transistor (FET) operated in the socalled source-follower mode, and the voltage change is measured at the source of this FET. Then, to prepare for the next charge packet, the reset transistor is pulsed again to remove the charge and restore the sense-node voltage to V_{RD} . An important parameter for this circuit is the conversion gain from electrons to output voltage. The signal from a charge packet of N electrons at the FET output is given by

$$V_{signal} = G \frac{qN}{C} = RN$$

where G is the voltage gain of the source follower (typicaly 0.7). The parameter R defined by this equation is the responsivity, or conversion gain, and is measured in volts/electron (V/e). A typical value of R for our CCDs is about 20 μ V/e.

There are two contributions to the noise of this circuit. The first is called reset noise, or kTC noise, and originates as a result of the reset operation. Because of





FIGURE 5. Top: depiction of the circuit elements in a CCD charge detection circuit. Middle: plan view of the device layout. Bottom: photograph of an output circuit.

thermal noise in the channel of the reset transistor, the sense node is not reset to precisely V_{RD} but rather to a random voltage whose mean is V_{RD} and whose variance is given by kT/C, where k is Boltzmann's constant and T is the absolute temperature. The equivalent variance



FIGURE 6. Plan view of a new version of the CCD output circuit using a *p*-channel junction field-effect transistor (JFET) as the sense transistor.

in charge is kTC, and for typical values of $C \approx 10$ fF the root mean square (rms) variation in charge is about 40 electrons. This noise charge is present on the sense node both before and after the transfer of the charge packet, and thus it is possible to remove it by measuring the output voltage both before and after the charge transfer and taking the difference of the two values. This procedure, called *correlated double sampling*, is standard practice for all CCD video processing.

The second contribution to the noise comes from the sense transistor itself. This noise cannot be removed, but it can be minimized by controlling the bandwidth of the video signal to no more than necessary to faithfully represent the signal information. To quantify this, we can represent the noise contributed by the sense transistor as the product of the mean-square spectral noise voltage v_n^2 and an effective bandwidth Δf , which is set by filtering and the correlated double sampling process. The rms noise voltage appearing at the correlated double sampling output is then $v_n \Delta f^{1/2}$. It is standard practice to express the noise of a CCD output in terms of an electron equivalent, which is done by dividing the rms noise voltage by the signal voltage produced by an electron. The noise in equivalent electrons is then $v_n \Delta f^{1/2}/R$.

It is clear that for lowest noise we need (1) sense FETs with low v_n and (2) small sense-node capacitance C. In our constant quest for low noise, we have shrunk the feature sizes of the output circuit in Figure 5 to minimize C and have made the output FET as quiet as is possible. Recently we began exploring an even more

compact and lower-capacitance output, as illustrated in Figure 6. Here the sense FET is a *p*-channel junction FET (JFET) and its gate is the n^+ charge-collection diode. By merging the charge-collection diode with the sense-transistor gate we reduce the capacitance by nearly a factor of two. The *p*-channel JFET turns out to have an output noise voltage that is somewhat smaller than the nMOSFET, and therefore the noise in equivalent electrons is expected to be better.

Figure 7 shows a summary of the best noise data obtained with CCD output circuits to date as a function of output data rate, and illustrates the trade-off between read noise and read rate. At pixel rates greater than 10^6 Hz the output circuit must have a second stage of amplification in order to drive the off-chip capacitance, and the data for these cases are shown as open circles.Included in red in this figure are preliminary measurements on the JFET output. This circuit is still in an early stage of development, but the limited data to date show values of 1.1 to 1.3 e⁻ rms from 70 to 500 kilopixels/sec. These data are much lower than our best MOSFET data, and the best reported anywhere.

CCD Imagers and Focal-Plane Arrays for Astronomy

The performance levels of our CCD technology in the three key areas—scale, quantum efficiency, and noise—mentioned in the last section attracted the attention of the astronomy community in the early 1990s. In 1994 we entered into a cooperative research and development



FIGURE 7. Summary of the best noise values obtained with Lincoln Laboratory CCDs. Included as red squares are preliminary results from the JFET version of the amplifier.



FIGURE 8. A 2048×4096 -pixel CCD imager mounted on a three-side-abuttable ceramic substrate with an attached flex-print for the input/output signals.

agreement (CRDA) with a consortium of observatories to develop a CCD with a format that was agreed upon by the consortium members. The original consortium consisted of six organizations (the Keck Observatory, Subaru Observatory, Anglo-Australian Observatory, European Southern Observatory, Canada-France-Hawaii Telescope, and University of Hawaii), to which additional groups were added in subsequent years. The consortium was led by Professor Gerard Luppino of the University of Hawaii. Collectively these organizations were able to fund a device development effort on a scale that was beyond their means individually. The device format agreed upon by the consortium was 2048×4096 pixels with a pixel size of $15 \times 15 \,\mu$ m, resulting in a chip size of 3.2×6.5 cm (19 cm^2) . The device was designed so that the pixel array came as close as practical (about 20 to 25 pixels) to the chip edge on three sides, and all the input/output leads, or wire bond pads, were arrayed along the fourth side. The resulting imager could then be closely abutted on three sides to other imagers, enabling arrays of $2 \times N$ devices. Figure 8 shows a photograph of a CCD mounted on a ceramic (AlN) carrier. A flexprint carrying the input/output signals is attached to a connector mounted on one end of the ceramic nearest the wirebond pads of the device. The blue color of the device is a result of the antireflection coating on the device surface.

This device is used in a number of focal-plane array detectors, the largest of which is the so-called CFH12k assembled at the University of Hawaii for the Canada-France-Hawaii Telescope on Mauna Kea, Hawaii. This array, the largest of its kind at over 100 megapixels when commissioned in 1998, comprises twelve devices arranged in a 2×6 configuration. Figure 9 shows a photograph of the array.

Images taken by this detector array are available on the CFHT web site and have been popularized by a series of calendars published by the observatory. The *Lagoon Nebula* and the *Horsehead Nebula* shown in Figure 10 are two examples of such imagery.

Figure 11 summarizes the history and rapid growth of multichip CCD arrays. The sizes in total pixel count



FIGURE 9. The Canada-France-Hawaii (CFH) 12k focal plane consisting of twelve closely abutted CCD imagers.



FIGURE 10. Left: a portion of the *Lagoon Nebula* (M8), taken by the CFH 12k CCD focal-plane array. The interstellar cloud lies 5200 light years from Earth in the constellation Sagittarius. Right: the *Horsehead Nebula* (IC434) is 1500 light years from Earth in the constellation Orion. It is part of a gigantic cloud of molecular gas and dust, and possibly the most famous nebula in the sky. (Images courtesy Canada-France-Hawaii telescope, J.-C. Cuillandre, Coelum.)

of several prominent focal-plane arrays are plotted versus year of introduction, together with an exponential curve, or Moore's Law, of focal-plane arrays, which illustrates a doubling of array pixel count every 2.5 years. Red circles in this figure show examples where Lincoln Laboratory CCDs have been used since the late 1990s in four observatories, as well as two cases planned for mid-2006 and early 2007 for the Pan-STARRS program. The Pan-STARRS imagers are of special type that are described in the next section. Further out, the figure indicates a planned array for the Large Synoptic Survey Telescope (LSST) scheduled for 2012, for which the detector manufacturer has yet to be determined.

Orthogonal Transfer CCDs

The figure of merit M in Equation 1 includes the image resolution $\Delta \theta$, and it is especially important to minimize this parameter because it enters as the squared reciprocal in M. For ground-based astronomy $\Delta \theta$ is determined not by the diffraction limit of the optics (for telescope apertures larger than about 10 cm) but by distortions due to atmospheric turbulence in the optical wavefront, as illustrated in Figure 12. Over the past two decades a technique known as adaptive optics, pioneered at Lincoln Laboratory and the Air Force Research Laboratory, has been increasingly used to compensate these wavefront aberrations and improve the resolution of a large telescope to nearly the diffraction limit [3]. Adaptive



FIGURE 11. Growth in CCD focal-plane array sizes from 1990 to an anticipated array in 2012 for the Large Synoptic Survey Telescope (LSST). Six arrays using Lincoln Laboratory CCDs are shown in red.



FIGURE 12. Depiction of the wavefront distortion arising from atmospheric effects. This distortion blurs the imagery of celestial objects to well below the diffraction limit of large telescopes.

optics measures the wavefront aberration by using a natural or artificial guide star as a beacon. The corrupted wavefront is then corrected by means of a deformable mirror. Typically, the artificial guide star is created by using a laser tuned for resonant backscattering from the so-called sodium layer, which resides at an altitude of about 90 km. Although this technique has yielded imagery with resolution in the milli-arcsec regime, it is expensive and only effective over a limited angular region in the vicinity of the laser beacon.

The lowest-order (but nevertheless significant) component of the wavefront corruption consists of a simple tilt, which manifests itself as an x-y deflection of the star images at the focal plane. The image of a point source thus dances randomly over distances of about one arc second at speeds of tens of hertz. Removing this component of distortion is sometimes done with a fast steering mirror, called a tip-tilt mirror, in the path of optical beam. Performing the tip-tilt correction alone leads to significantly better resolution, as low as a few tenths of an arc second, though not as good as a laser-guide-star adaptive optics system.

The mechanical tip-tilt systems themselves suffer from high cost, complexity, and optical loss, so it was natural to try to achieve this capability electronically within an image sensor. Conventional CCDs can shift charge along one direction, but to shift charge in all directions in order to track image motion required a novel CCD. Such a device, called the orthogonal transfer CCD (OTCCD), was developed at Lincoln Laboratory in the mid-1990s in collaboration with John Tonry, then a member of the Department of Physics at MIT [4].



FIGURE 13. Depiction of the gate architecture and charge flow of a conventional three-phase CCD (left) and of two types of orthogonal transfer CCDs, or OTCCDs (right).

OTCCDs have a distinctly different gate-electrode geometry in comparison to conventional CCDs. Figure 13 illustrates the gate arrangement of a three-phase CCD and two types of OTCCDs. In the three-phase CCD a pixel is defined by three gates or phases along one dimension and by so-called channel stops along the other. Channel stops are narrow regions with high levels of a *p*-type dopant to create a barrier potential to the electron charge packets. Depending on the sequence of voltages applied to the three gates, a charge packet can be transferred in either direction indicated by the arrow. The OTCCDs illustrated on the right require four phases per pixel but can transfer charge either horizontally or vertically. To transfer charge along one direction, one of the phases must be biased to a low potential (shaded dark in the illustrations), which renders it blocking to electrons and effectively makes it a channel stop. The remaining three phases can then be clocked to transfer charge.

Our first OTCCD capable of acquiring useful astronomical data was a 512 × 512-pixel frame-transfer device, depicted in Figure 14. The imaging array consisted of the type-1 pixel design, while the frame store was a conventional three-phase design. To use this device to compensate for image motion, a user needs to have a beacon in order to measure the motion of the target. This was done by selecting a sufficiently bright nearby star falling on the frame-store region, and then reading a small window of pixels around this guide star at a rate (typically 10 to 30 Hz) sufficient to track its image motion. This information is then used to update the OTCCD pixel shifts to maintain approximate registration of the pixel charge with the image motion.

This device was tested at the Michigan-Dartmouth-MIT 2.4 m observatory on Kitt Peak, Arizona, in 1996 [5]. Figure 15 shows examples of the imagery with and without motion compensation. The object is a small portion of the star cluster M71, and the exposure time in this case was 150 seconds. We show this result as a surface plot rather than a conventional intensity image to emphasize the fact that the active tracking not only improves the resolution (full width at half maximum = 0.50 arcsec versus 0.73 arcsec without orthogonal transfer shifting), but also improves the signal-to-noise ratio (SNR). Stars that are barely perceptible above the noise background on the left side of the image are easily detected on the right side. The SNR improvement here is 1.8×, the significance of which can be measured not



FIGURE 14. Depiction of the first use of an OTCCD for motion compensation in an astronomical application. The upper portion of the device has OTCCD pixels that are shifted to track the random image motion arising from atmospheric wavefront distortion. The lower portion of the device is operated independently as a star tracker at frame rates sufficient to track the image motion and provide feedback to shift the OTCCD pixels.

only in scientific terms but also in monetary terms. For direct sky imaging, where the sky background sets the noise floor, the SNR scales with the diameter D of the telescope. Thus a 1.8× increase in SNR is equivalent to an 80% increase in the effective diameter of the telescope. Since telescope costs scale roughly as D^3 , the economic benefit of an OTCCD can clearly be substantial. Also worth noting is the fact that orthogonal transfer shifting compensates not only the image motion from the atmospheric effects just mentioned but also such problems as telescope shake and guiding errors.

We sidestepped an issue in the earlier discussion of the tip-tilt correction. In how wide a field of view does the wavefront curvature remain correlated? This value is called the isokinetic angle, and values of a few arcsec are quoted in the literature, assuming wavefront distortions arising from the entire column of air up to ten kilometers. Clearly this value will limit the distance between guide star and imaging pixels and thus the useful size of a sensor of the type depicted in Figure 14. The measurements at the Michigan-Dartmouth-MIT observatory,



FIGURE 15. Surface plot of imagery from a portion of the star cluster M71. The image on the left was taken with no compensation shifting of the OTCCD pixels, while that on the right utilized feedback from fast guidestar tracking in the frame store.

however, showed that the wavefront tilt was almost uniform across the entire device, an angular distance of 2.5 arcmin. This suggests that the wavefront tilt was mostly originating close to or within the telescope dome.

Orthogonal Transfer Array and Pan-STARRS

For wide field-of-view imaging (i.e., greater than the isokinetic angle), a new OTCCD architecture is necessary. Basically, the ideal image sensor should be an array of modest-sized OTCCDs, each with a field of view no larger than the isokinetic angle. For such a device, the wavefront tilt will in general vary among the cells, so that each OTCCD will need to be independently controllable to optimally track image motion. Such a device was proposed in 2000 [6], and development of the first prototypes began at Lincoln Laboratory in 2003 [7]. Figure 16 illustrates the principal features of this device, which is called an orthogonal transfer array (OTA). This figure depicts a chip with an 8×8 array of OTCCDs, each driven by the requisite four parallel clock lines (P1 through P4), a three-phase serial readout register (S1 through S3), and an output amplifier. What differentiates this device from the previously described CCDs is that the parallel clocks and the video readout are under the control of a set of logic circuits adjacent to each OTCCD. This logic is addressed and set with control



FIGURE 16. Depiction of the orthgonal transfer array (OTA). This device is an 8×8 array of independent OTCCDs, each comprising about 600 × 600 pixels and controlled by negative MOS (NMOS) logic.



FIGURE 17. Operation of an OTA with some cells assigned to tracking guide stars and the remainder acquiring science imagery.

bits from an off-chip controller to enable independent shifting and readout of each OTCCD.

Support for the development of this device was approved in 2003 as part of a program called Pan-STARRS (Panoramic Survey Telescope & Rapid Response System) [8, 9]. This system is being developed at the Institute for Astronomy at the University of Hawaii under a grant from the Air Force Research Laboratory. The currently planned configuration for Pan-STARRS is a set of four co-aligned 1.8 m telescopes with a 3° field of view, each equipped with a large focal-plane array of OTAs (described below). The primary mission is to map the entire sky visible from Hawaii on a regular schedule in

order to detect moving objects—in particular, potentially hazardous asteroids and comets. The wide field and high sensitivity of the system enables a variety of other astronomical studies as well.

Figure 17 illustrates the operation of the OTA. As described earlier in this section, the motion of guide stars must be monitored in order to provide the pixel shift data. In this architecture some cells are assigned to image guide stars for measuring the local image translation, while the remainder acquire the science images. The guide-star cells will, of course, lead to gaps in the science imagery, as will nonfunctional cells and other non-active regions of the focal plane. Astronomers are accustomed to dealing with these issues by using a strategy of stacking multiple images taken at various displacements around the region of interest. In Pan-STARRS, the four telescopes will be imaging the same sector of the sky so that the multiple images can be recorded simultaneously, thereby improving the sky coverage rate.

The first step in imaging a sector of sky is to select those cells, perhaps four or five, which happen to contain sufficiently bright stars to be used as guide stars. These cells will image and read out a small subarray of pixels around the guide star, and from these data the centroids of the stars will be used to construct a map of the image deflection field over the chip field of view. "Sufficiently bright" thus means stars that yield imagery of sufficient SNR to enable reasonably precise centroiding. This information, in turn, is used to address and



FIGURE 18. Packaged orthogonal transfer array showing device side (left) and bottom (right). The device measures 5×5 cm, and the package enables close abutting to other devices on all four sides.



FIGURE 19. Depiction of the Pan-STARRS gigapixel focalplane array comprising 64 OTAs. Each side of this array measures 15.6 inches.

update the science cells with the appropriate pixel shifts. The rate at which the cycle of guide-star read and science-cell update occurs will lie in the range of 10 to 30 Hz. At the conclusion of the integration period the cells are read out one row at a time through eight video lines that service the eight cells in each column.

The first prototype OTAs were designed and fabricated in the Laboratory's Advanced Imaging Technology group in collaboration with the University of Hawaii. The device measures 5×5 cm, or 25 cm², and is among the largest that we have made. Apart from the challenge of making a device of this size with reasonable yield was the fact that we had never placed control logic on any CCD imager. Budget and schedule constraints prevented us from developing a process for incorporating CMOS logic into the CCD process. Instead we decided to use a much simpler process called negative MOS (NMOS), which could be grafted onto the CCD process with little impact to the CCD. NMOS, which was the principal logic process until the early 1980s, consumes much more power than CMOS, but the modest transistor count needed to build the logic functions (39 MOSFETs in each logic block) meant that we could keep the power dissipation to an acceptable level.

Another feature of the device was that it needed to be abuttable on four sides with minimal seam loss and dead space, in contrast to the three-side-abuttable 2048 \times 4096 CCDs described earlier. This requirement was mostly reflected in the package design. Figure 18 shows a photograph of an OTA on the Pan-STARRS package, and a photograph of the bottom of the package. A molybdenum plate serves as the base of the package. The CCD is epoxied to the front surface of this plate, while the back has three threaded holes for alignment feet and clips for attaching a wirebond ceramic pin grid array (PGA). The feet enable kinematic mounting of the package to the focal-plane assembly as well as the thermal path for cooling the device.

The ceramic PGA provides bond pads for the chip input/output and pins for attaching a flexprint. The bond pads occupy a ledge that protrudes approximately 1.7 mm beyond the edge of the die/molybdenum base. Because this ledge and the corresponding pad real estate on the chip contribute a significant amount to the total focal-plane dead space, we elected to keep all input/output on one edge.

Figure 19 illustrates the Pan-STARRS OTA focalplane array, which will consist of 64 OTAs. Collectively this array will comprise 1.4 gigapixels, and the CCD array and its electronics are termed GPC1 (gigapixel camera 1). When it is commissioned in mid-2007 it will be the largest such astronomical detector in the world by over a factor of four, as indicated earlier in Figure 11.

Device Performance

Our first prototype OTA wafer lot was completed in mid-2004 and underwent evaluation both at Lincoln Laboratory and at the University of Hawaii. Devices from the first lot performed all the basic functions expected, but tests revealed some problems at low signal levels that needed correcting before we began fabricating devices for GPC1. The two principal problems were higher noise (10 to 20 e⁻) than our goal (5 e⁻), as well as a low level of spurious charge originating in the logic and output circuits. Nevertheless, the prototype devices



FIGURE 20. The 360-megapixel array of 16 OTAs known as test camera 3 (TC3) is shown under a metrology microscope.



FIGURE 21. Imagery from an individual OTA cell (590 \times 598 pixels) demonstrating the four-direction charge-shifting capability. A fixed light spot was focused on the device, and the clocks were programmed in a pattern that generated the image.

turned out to be useful for building an engineering array known as test camera 3 (TC3), which consists of a 4×4 array of devices that will be used for shakedown tests of the focal-plane assembly procedures, camera electronics, signal processing, and telescope. The TC3 pixel count alone (360 megapixels) places it at nearly the largest extant focal-plane camera (see Figure 11). Figure 20 shows a photograph of this array undergoing flatness measurements under a metrology microscope.

The performance issues with the prototype devices were successfully addressed in a redesign of the OTA in mid-2005, and two wafer lots (48 wafers) have been fabricated to supply GPC1. Most of these devices have been packaged and delivered to the University of Hawaii. Figure 21—an image from an individual cell—demonstrates the imaging capability and two-dimensional shifting capability of the OTA. This example is not the result of the Lincoln Laboratory logo imaged onto the device. Rather, it was created by focusing a fixed light spot onto a small group of pixels. The CCD clocks were then shifted to "paint" the image onto the cell. The image in Figure 22 is from a full OTA operating in a cryostat at -70° C.



Summary

For over thirty years CCD imager technology at Lincoln Laboratory has steadily evolved to the point today where devices with read-noise levels approaching 1 eand with high quantum efficiency over a broad range of wavelengths from the ultraviolet out to 1 μ m in the near infrared are now routine. The high device yields obtainable from the Laboratory's Microelectronics Laboratory enable chip sizes well in excess of 20 cm^2 and resolution greater than 20 megapixels. These devices have played an important role in space surveillance programs here at the Laboratory as well as serving the astronomy community, both of which have essentially the same requirements for large high-sensitivity sensors. Our collaboration with several observatories led by the University of Hawaii has resulted in several large focal-plane arrays of CCDs deployed around the world.

Our most recent joint effort with astronomers began ten years ago with the conception and development of a novel device, the orthogonal transfer CCD, or OTCCD, which has great promise for improving image quality in ground-based observatories. Currently we are well into deliveries of a new device based on the OTCCD called the orthogonal transfer array, or OTA. A 64-OTA focal-plane array of 1.4 gigapixels will be built early next year for the Pan-STARRS program at the University of Hawaii and will be, by over a factor of four, the largest such array in the world.

Acknowledgments

We would like to thank Professor Gerard Luppino at the University of Hawaii for his support of our CCD development. Special thanks are due to Professor John Tonry, who has played a key role in the development of the OTCCD and Pan-STARRS OTA devices, and without whose support and efforts these unique devices would not have been possible. We also wish to thank Robert Reich and Daniel O'Mara, who have contributed to the *p*-channel JFET sense amplifier work, and Bernard Kosicki for his technical contributions and support. Finally, we want to acknowledge the many technicians in the Microelectronics Laboratory for their efforts in making these challenging devices.

REFERENCES

- G.H. Stokes, C. von Braun, R. Sridharan, D. Harrison, and J. Sharma, "The Space-Based Visible Program," *Linc. Lab. J.* 11 (2), 1998, pp. 205–238.
- G.H. Stokes, F. Shelly, H.E.M. Viggh, M.S. Blythe, and J.S. Stuart, "The Lincoln Near-Earth Asteroid Research (LIN-EAR) Program," *Linc. Lab. J.* 11 (1), 1998, pp. 27–40.
- 3. The Spring 1992 issue of the *Lincoln Laboratory Journal*, volume 5, no. 2, is devoted to the subject of adaptive optics.
- B.E. Burke and J.L. Tonry, "Recent Developments with the Orthogonal-Transfer CCD," SPIE 3019, 1997, pp. 233–240.
- J.L. Tonry, B.E. Burke, and P.L. Schechter, "The Orthogonal Transfer CCD," *Publ. Astron. Soc. Pac.* 109, Oct. 1997, pp. 1154–1164.
- N. Kaiser, J.L. Tonry, and G.A. Luppino, "A New Strategy for Deep Wide-Field High Resolution Optical Imaging," *Publ. Astron. Soc. Pac.* 112, June 2000, pp. 768–800.
- B.E. Burke, J. Tonry, M. Cooper, G. Luppino, G. Jacoby, R. Bredthauer, K. Boggs, M. Lesser, P. Onaka, D. Young, P. Doherty, and D. Craig, "The Orthogonal-Transfer Array: A New CCD Architecture for Astronomy," *SPIE* 5499, 2004, pp. 185–192.
- 8. Pan-STARRS, http://pan-starrs.ifa.hawaii.edu/public.
- N. Kaiser, H. Aussel, B. Burke, H. Boesgaard, K. Chambers, M. Chun, J. Heasley, K. Hodapp, B. Hunt, R. Jedicke, D. Jewitt, R. Kudritzki, G. Luppino, M. Maberry, E. Magnier, D. Monet, P. Onaka, A. Pickles, P.H. Rhoads, T. Simon, A. Szalay, I. Szapudi, D. Tholen, J. Tonry, M. Waterson, and J. Wick, "Pan-STARRS: A Large Synoptic Survey Telescope Array," *SPIE* 4836, 2002, pp. 154–164.



BARRY E. BURKE

is a senior staff member in the Advanced Imaging Technology group. He received a B.S. degree in physics from the University of Notre Dame and a Ph.D. degree in applied physics from Stanford University. He joined the Laboratory in 1969, and has been working on CCD imagers since 1975. He received the Lincoln Laboratory Technical Excellence Award in 2001, and is a Fellow of the IEEE.



JAMES A. GREGORY

is an assistant leader of the Advanced Imaging Technology group. He has worked on CCDs and avalanche photodiodes since joining Lincoln Laboratory in 1987. His particular interests include processing of siliconbased devices and developing back-illuminated imagers. Prior to joining the Laboratory, he worked on solar cell development at Mobil Solar Corporation. He holds S.B. and Sc.D. degrees in materials science from MIT.



MICHAEL COOPER

is an associate staff member in the Advanced Imaging Technology group, where he is involved in the design, characterization, and simulation of CCD sensors. He graduated with special honors with a B.S. degree in electrical and computer engineering, and *summa cum laude* with a B.S. degree in applied mathematics, both from the University of Colorado. He has also completed coursework toward an S.M. degree in electrical engineering at MIT.



ANDREW H. LOOMIS

is an associate staff member with the Advanced Imaging Technology group. He supervises the production of specialized back-illuminated CCDs and silicon sensors and develops advanced wafer-processing techniques for various silicon imagers. His current research interests are in wafer bonding and specialized back-end CCD fabrication techniques. Before joining Lincoln Laboratory in 1986, he worked two years for at GCA Corporation in Bedford, Massachusetts, developing laser scanning systems for defect identification. In 1984, he received a B.S. degree in electronic engineering from Wentworth Institute of Technology in Boston.

• BURKE ET AL. CCD Imager Development for Astronomy



DOUGLAS J. YOUNG

is an associate staff member in the Advanced Imaging Technology group. His research interests are in the area of semiconductor process development related to the fabrication of CCD imagers and photodiode arrays. He also provides engineering support to the photolithography and etch areas of the Microelectronics Laboratory. He joined Lincoln Laboratory in 1989 after working for two years as a technical instructor for MIT's Microelectronics Educational Facility. He has a B.S. degree in electrical engineering from the University of Vermont.



THOMAS A. LIND

is an associate staff member in the Advanced Imaging Technology group. He received a diploma in Aeronautical Technical Sciences from the East Coast Aerotechnical School, Bedford, Mass., in 1964. In 1968 he joined the Applied Physics group at Lincoln Laboratory, where he worked on IV-VI semiconductor lasers, III-V materials evaluation, and GaAs/GaAlAs laser fabrication. He was involved in the design, fabrication, and evaluation of early GaInAsP/InP lasers, participating in the development of the first continuouswave device and the first long-lived device. In recent years he has evaluated the optical performance of CCD imagers.



PETER DOHERTY

is an associate staff member in the Advanced Imaging Technology group. He joined Lincoln Laboratory in 2003. His current work includes the design and construction of electronic systems for the testing, evaluation, and deployment of CCDs and CCD camera systems. Prior to joining the Laboratory he developed CCD-based instrumentation for use in astronomy at the University of Washington. He has been involved in CCD system design and development engineering since 1988. He received a B.A. degree in physics from Hampshire College in 1986.



PETER DANIELS

is an associate staff member in the Advanced Imaging Technology group. He is responsible for packaging CCD and APD imagers. In addition, he oversees packaging of devices for various groups in the Laboratory. He is a graduate of Northeastern University, where he received a B.S. degree in engineering technology. He is a member of the Sigma Epsilon Rho honor society and has been at the Laboratory since 1964.



DEBORAH J. LANDERS

is a project technician for the Advanced Imaging Technology group. She packages Laboratory-processed semiconductor CCDs used in ground-based and space-based astronomy, and devices used in ladar ranging systems. Before joining Lincoln Laboratory in 1984, she packaged semiconductors for missile systems at Microwave Associates in Burlington, Massachusetts.



JOSEPH CIAMPI

is a specialist in the Advanced Imaging Technology group. He provides engineering support in the process development and fabrication of CCD imagers and CMOS devices. He is also the diffusion area engineer of the Microelectronics Laboratory. He has been at Lincoln Laboratory since 1982.



KAY F. JOHNSON

is an engineering specialist in the Advanced Imaging Technology group. She began working at Lincoln Laboratory in 1979 with the Microelectronics group. She is responsible for integrated-circuit computer-aided design (CAD) of CCD imagers, photodiodes, package substrates, and special process development projects. She has an associate degree from Mount Wachusett Community College.



PETER W. O'BRIEN

manages the operation of the Optical Coating Laboratory within the Quantum Electronics group, providing an Institute-wide resource for consulting, designing, R&D, and manufacturing of specialized thin films for a variety of needs. Before joining the Laboratory in 1996 he worked at MIT's Francis Bitter National Magnet Laboratory in the magnet design group. He received a B.S. degree in geological science from Salem State College in 1990.