

A Review of Night Imaging Technologies- Innovations for the Visible to Long Wave Infrared Systems

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Keywords: Infrared, detectors, image intensification, microchannel plates

The history of night-imaging technologies can be divided into the categories of image intensifiers and solid state detectors. Image intensifiers amplify a visible/near-infrared image and subsequently convert this amplified signal into a visible screen image. The solid state sensors come in a variety of formats. The solid state design typically, but not always, has an active semiconductor layer that can absorb infrared radiation to generate electrons and holes. High-end IR sensors are usually HgCdTe diodes, grown and processed as either single or multiple band devices that operate at cryogenic temperatures. Other formats include uncooled bolometers, MSMs, PINs and APDs. This paper will focus on technologies that historically have been driven by Army needs: a brief overview of image intensifier (I^2) technology and HgCdTe solid state detectors.

The first version of image intensifiers (Gen 0) consisted of a Ag-O-Cs cathode enclosed by a glass/metal vacuum envelope, Fig. 1. Electrons generated at the cathode are accelerated using an applied field. The device, operated at high vacuum and high voltage (16V), had remarkably high resolution, 57 to 72 line pairs/mm; this metric of resolution denotes the line pairs per millimeter that can be resolved when focused on the photocathode. The electrons pass through field-forming electrodes and impinge upon a phosphor screen. It had an electronic gain of 1 and a photo-response (PR) of about $60\mu\text{A/lumen}$.

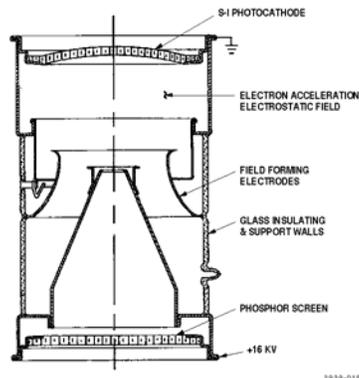


Fig. 1

The Gen 0 image intensifier, because of the low gain, required additional infrared lighting to operate and, as such, left the user somewhat vulnerable as a target for an enemy equipped with night vision capability. What was needed was a device with more gain for covert military operations. Gen 0 production startup began in 1959 and continued until about 1970. During this time significant technological innovation was made in the next-generation image intensifier (Gen 1).

The Gen 1 I^2 device also employed a glass wall cylinder with glass-to-metal seals. A Sb-K-Na-O cathode was employed. Unlike Gen 0, Gen 1 employed fiber optic faceplates for the cathode and the screen which permitted three tubes to be coupled together as a triplet to produce high gain. Each individual Gen 1 diode had a luminance gain of about 70, although the resolution was comparable, at 57 lp/mm. The Gen 1 systems were passive – they didn't need additional infrared lighting. The night sky illumination was bright enough to conduct nighttime operations. During the 1960s the Gen 1 device was used successfully in Vietnam. Overlapping this period the first microchannel plate (MCP) was developed.

The development of the microchannel plate (MCP) in the late 1960s brought on the second generation of image intensifiers. The MCP multiplied electrons, which eliminated the need for three-stage light

amplification and reduced the size, weight, and distortion of the image intensifier tube. With the MCP, night vision goggles and handheld viewers became possible. The MCP also provided much more robust operation when bright lights were in the field of view. The luminance gain of the Gen 2 sensor was markedly improved to 7-10,000 and the resolution was 28-36 lp/mm. Although the Gen 2 still required a hard vacuum, the operating voltages of the active components were much lower than in previous generations. Proximity-focused tubes using an MCP to produce high gain made the Gen 1 "triplets" obsolete and greatly reduced system size and weight, see Fig. 2

Third generation image intensifiers were developed in the mid-1970s and became available during the early 1980s. Gen 3 introduced two major technological improvements: a gallium arsenide (GaAs) photocathode and the ion barrier coating to the MCP. The GaAs photocathode increases the tube's sensitivity to light from the near-IR range of the spectrum, and thereby enables it to function at greater detection distances, and improves system performance under low-light conditions.



Fig. 2

Application of a metal oxide ion barrier to the MCP is required to protect the gallium arsenide photocathode from ion feedback originating in the MCP, thereby enabling adequate operational lifetime (i.e., 4,000 to 10,000 projected hours). The luminance gain of the Gen 3 sensors was improved to 20-80,000 and the resolution was improved to 45-72 lp/mm. State-of-the-art Gen 3 tubes provide high PR, gain, S/N and resolution for the highest quality Night Vision Goggles (NVGs). The remainder of the paper deals with the different methods to grow HgCdTe crystals for solid state sensors and then does on to discuss the technological development of the HgCdTe sensors. The growth of HgCdTe has evolved along with other semiconductor materials technologies over the past 40 years. Three principal methods have been developed: bulk, liquid phase epitaxy and vapour phase epitaxy.

Bulk growth of HgCdTe proved very difficult due mainly to the high vapor pressure of Hg at the crystal melting point, about 950°C. Early experiments and a significant fraction of early production was done using a quench-anneal or solid-state recrystallization process. In this method the alloy was reacted from purified starting materials and then rapidly quenched. Rapid quenching was needed to prevent segregation of HgTe from CdTe which have significantly different melting temperatures. The result of quenching was a highly polycrystalline solid. Annealing near the melting point was used to grow larger grains.

Bridgman growth, under high pressure to contain the Hg pressure, was attempted for several years near the mid-70s. At the same time, solvent growth methods were initiated which could be carried out at reduced temperature. In one case the solvent used was Te. Solvent growth also provided an additional purification step through zone refining as the solution was passed through the solid phase. By the late 70s bulk growth

was sufficiently reproducible to support the production start-up of first generation LWIR photoconductive HgCdTe array production.

Bulk growth produced thin rods of HgCdTe material, generally 8-to-12 mm in diameter and about 20 cm in length. This material could be used for linear array production, but the vision of larger two-dimensional arrays could not be realized with this method. Another drawback to bulk material was the need to thin the bulk wafers, generally cut about 500 μm thick, down to the final device thickness of about 10 μm . Polishing the wafers, mounting them to suitable substrates, and polishing to the final device thickness was labor intensive.

In the early 90s, bulk growth of HgCdTe was phased out for the routine production of first generation photoconductive devices. Bulk growth has been replaced by liquid-phase epitaxial growth (LPE) which is reviewed following a description of substrates for epitaxial growth below.

Epitaxial growth of thin layers of HgCdTe for infrared detector array fabrication requires a suitable substrate. CdTe was used initially, since it was available from commercial sources in reasonably large sizes. Unlike HgCdTe, CdTe bulk crystal growth is not limited by high Hg overpressures. The $\langle 111 \rangle$ crystal orientation was determined to be favorable for smooth growth by the LPE technique. For vapor-phase growth, the $\langle 211 \rangle$ orientation gave preferential growth with the MBE technique.

CdTe has good physical properties for an infrared detector substrate. First of all it is transparent out to 30 μm , so that devices with the IR photon-flux incident on the backside are readily made without having to remove the substrate. Second, CdTe is not a potential dopant of the epitaxial film. Third, CdTe is more robust than HgCdTe crystals, although still much more fragile than silicon or germanium. The main drawback to CdTe as an epitaxial substrate is that it has a few percent lattice mismatch with LWIR and MWIR HgCdTe. This mismatch caused LPE-grown films to be morphologically rougher than desired. By the mid-80s it was demonstrated that the addition of a few percent ZnTe to CdTe could create a lattice-matched substrate. CdZnTe has been the principal substrate in use since that time. It is available from a variety of vendors today. Following boule growth the CdZnTe material is polycrystalline, but with very large grains. An effective method for seeding the growth to produce oriented single-crystal boules had not been developed. The largest grain is selected and oriented for sawing into wafers. After sawing, the wafers are polished in preparation for epitaxial growth. Defect densities of CdZnTe substrates are routinely in the low $10^4/\text{cm}^2$ range as determined by etch pit counts.

Silicon substrates are the "holy grail" of substrate development. Silicon is strong, large, and has no thermal coefficient of expansion mismatch with silicon readouts. The rewards for the quest are matched by the substantial difficulties of growing II-VI materials on silicon. Work on silicon substrates began in the mid-80s and although progress has been slow it is still very promising. Buffer layers are needed to prime the surface prior to epitaxial growth. Defect densities of silicon substrates prepared for epitaxial growth of HgCdTe are typically in the $10^9/\text{cm}^2$ range—improved by an order of magnitude from a decade ago. Still this technology needs additional development for use in applications which require high pixel operability, particularly for LWIR alloy compositions.

Liquid-phase epitaxial (LPE) growth of thin layers on CdTe substrates began in the early to mid 70s. CdTe substrates could be grown in large diameters because Hg overpressure was not a limiting consideration. Initially, Te solutions with dissolved Cd and saturated with Hg vapor were used to efficiently grow HgCdTe layers with thickness suitable for direct device fabrication. Cd has a high solubility in Te. This allowed small-volume melts to be used with the slider technique which did not appreciably deplete during the growth run. Surface wetting and melt decanting were early problems however.

Experiments with Hg-solvent LPE began in the late 70s, a couple years after the initial work with Te solutions. Because of the limited solubility of Cd in Hg, the volume of the Hg melts had to be much larger than Te melts in order to minimize melt depletion during layer growth. This precluded the slider growth approach. Hg-melt epitaxy has been developed using large dipping vessels.

LPE growth struggled in the early 80s as growers learned a series of important lessons in order to reduce surface morphology defects and achieve uniform, smooth epitaxial layers. One of these was the importance of having precise substrate orientation. A second was the need for lattice matched substrates which were developed by adding a few percent of ZnTe to CdTe.

Diodes fabricated on early LPE material were made by ion implantation into p-type layers which had been annealed to generate Hg-vacancy acceptors. By the mid-80s, LPE growers learned how to achieve extrinsic p and n-type doping, allowing the growth of junctions using p- and n-type doped melts. This resulted in greatly improved device quality and set the stage for the production of both first- and second-generation devices from LPE material.

LPE growth technology is now very mature for production of both first- and second generation tactical detectors. Hundreds or thousands of layers are routinely grown each year for a wide variety of production programs as well as technology demonstration and technology development tasks. Even so, LPE technology is limited for a variety of advanced HgCdTe structures to be described later in this paper. These devices require more elaborate layer structures than a p-n junction. The gradient in x-value, a consequence of the partial depletion of Cd during the operation, can generate a barrier to carrier transport in certain cases. LPE also typically melts off a thin layer of the underlying material each time an additional layer is grown. These limitations have provided an opportunity for vapor phase growth to supplant LPE technology for growing advanced device structures in the near term. An overview of vapor-phase growth is described in the next section.

Vacuum evaporation growth of HgCdTe was explored as early as the late 1960s by IBM. Bulk HgCdTe was also assembled into sputtering targets and sputtered films were evaluated in a number of laboratories. Nothing came of these early efforts. Temperature-gradient-induced vapor transport has also been used to grow films in a few laboratories over the years as well.

The modern vapor-phase era began in the early 80s with parallel efforts using metal-organic chemical vapor deposition and molecular beam epitaxy. By this time both of these methods had been well established in the III-V semiconductor materials arena and were adapted for growing II-VI compounds and alloys.

Over the past fifteen years there have been a variety of groups who have explored MOCVD and MBE techniques. On the MOCVD front a wide variety of metal-organic compounds were developed along with a number of reaction-chamber designs. MBE technology, in parallel, had to address specially designed Hg-source ovens to overcome the low sticking coefficient of Hg at the growth temperature. A few attempts were made using hybrid systems — MOMBE for example, where metal-organic sources were used in an MBE chamber.

At this time, MBE has become the dominant vapor-phase growth method for HgCdTe. Although the quality of MBE material is not yet on a par with LPE, it has made tremendous progress in the past decade to the point where a variety of high-background device formats have been successfully demonstrated using this growth technique. Keys to this success have been the ability to dope layers both p- and n-type, and the reduction of etch pit densities by an order of magnitude or more from a range of $10^7/\text{cm}^2$ to below $10^6/\text{cm}^2$. MBE is now the preferred method for growing complex layer structures for two- and three-color detectors as well as for avalanche photodiodes (APDs). It is anticipated that MBE will phase into production for a subset of applications in the next few years.

HgCdTe Infrared Detector Devices

The popularity of HgCdTe detectors is made possible by their flexibility in spectral response over a wide span of the infrared regions of interest. HgCdTe spectral flexibility is illustrated in Figure 3 which shows the spectral quantum efficiency of a variety of HgCdTe devices, including photoconductors (PC), photodiodes (PV), and avalanche photodiodes

(APDs). Photodiode technology is being vigorously extended to wavelengths beyond 12 μm . In the next few years, photodiodes will largely replace photoconductors at wavelengths out to about 20 μm . Single element photoconductors used in spectrometers to about 25 μm at liquid nitrogen temperature will continue to occupy that niche application.

Three generations of HgCdTe devices have been successively developed. Photoconductors, the first generation of HgCdTe devices, entered production in the late 70s following the establishment of reproducible bulk growth techniques and anodic-oxide surface passivation.

In parallel work had begun on photovoltaic device technology which took another decade to reach volume production. At this time, third-

generation devices are in development and demonstration programs. Each of these will be described below.

Photoconductors

First generation HgCdTe detectors consist of linear arrays of photoconductive devices. Good quality photoconductors can be fabricated by applying metal electrodes to pure n type material, thinned to approximately 10 μm.

Characteristics of a basic LWIR photoconductive HgCdTe are:

- 50-100 Ω impedance per square
- 10⁵ V/W at 1 mA bias for a 50'50 μm device
- D* about 80% of background limit
- Photon noise level of a few nV/√Hz

These detectors are tractable with low-noise preamplifiers, generally having emitter-coupled bipolar front ends. However, because of their low impedance and low noise, photoconductors have not been deployed with focal plane readouts operating at 80K—standard silicon bipolar devices do not operate below about 150K. These factors have limited the scope of first generation devices to linear arrays with typically fewer than 200 elements. Within this scope the industry has produced tens of thousands of thermal imaging systems using PC arrays.

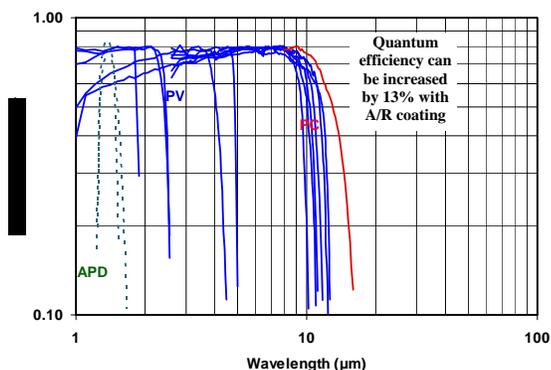


Fig 3 Spectral coverage of HgCdTe spans short (1-3μm), mid (3-5), and long (8-14) wavelength infrared

Photodiodes

Second-generation HgCdTe devices are two-dimensional arrays of photodiodes. Photodiodes having modest impedance (resistance-area product or ROA) of 10 Ωcm² can be mated to silicon readout arrays with indium bump bonds at the pixel level. First demonstrated in the mid-70s²⁰, indium bump bonding of readout electronics provides for multiplexing the signals

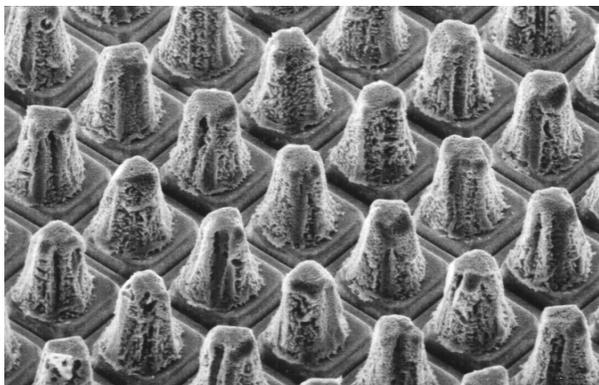


Fig 4

from thousands of pixels onto a few output lines, greatly simplifying the interface between the vacuum-enclosed cryogenic sensor and the system

electronics. In a general sense, the signal-to-noise ratio of a sensor will improve with the square-root of the number of detector elements in an array—to the extent that they can collect proportionally more signal from the scene. Today, millions of pixels are connected to millions of amplifiers/integrators in the unit cells of readout circuits. Figure 4 shows a region of pixels on a 1024'1024 HgCdTe array with indium bumps deposited for bump bonding to a readout.

In spite of the tremendous impetus offered by large PV array development, photovoltaic HgCdTe took many years to emerge from laboratory demonstrations.

The structure of a mesa-etched photodiode is illustrated in Figure 5. The key technology needed to make photovoltaic devices possible was surface passivation. Based on silicon's success, passivation efforts were initially focused mainly on oxides. Anodic oxide was adequate for photoconductors, but the resulting surfaces were heavily accumulated with fixed positive charge. Although the surface shunt this produced did reduce the photoconductive signal, the positive charge minimized surface recombination of minority carriers and that was beneficial. Applied to photodiodes on the other hand, anodic oxide shorted out the devices by inverting the p-type surface.

Photovoltaic device structure

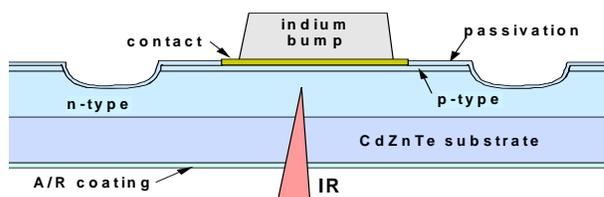


Fig 5

Silicon oxide was employed for passivation of HgCdTe in the early 80s based upon low temperature deposition using a photochemical reaction. SiO₂ could be deposited with low surface state densities and excellent PV device properties were demonstrated with this passivation material. However, the excellent surface properties could not be maintained when the devices were heated in vacuum for extended periods of time, a procedure required for good vacuum packaging integrity. These oxides were also subject to surface charge buildup when operated in a space-radiation environment.

ZnS, a common antireflection coating for PC HgCdTe, was used with intermittent success but also lacked stability during vacuum baking. Many other materials were also tried with varying success, including oxides, sulfides, and fluorides.

With the advent of CdTe passivation in 1987, HgCdTe photodiodes could finally be reliably passivated. CdTe passivation is stable during vacuum packaging bake cycles and shows little effect from the radiation found in space applications. Diodes passivated with CdTe have been demonstrated which do not show a variation in ROA with diode size, indicating that surface perimeter effects can be inconsequential. This development has made possible the full-scale production of second-generation devices.

Second-generation HgCdTe photodiodes are now being demonstrated and produced in both scanning and staring formats. For scanned infrared imaging systems the two-dimensional format allows signal averaging through time-delay-and-integration (TDI) signal processing, either on or off the focal plane. Scanning second-generation sensors improve both sensitivity and spatial resolution through the use of more detector elements in both scan and cross-scan directions. Scanning array configurations have increased pixel counts by a significant factor over first-generation arrays—with arrays of 240x4, 288x4, and 480x4 replacing 60, 120, or 180 element arrays.

Staring array configurations have increased the number of pixels even more dramatically over first-generation infrared systems. This has had the largest impact on short- and medium-wavelength applications where most or all of the frame time can be used for signal integration. In the long

wavelength spectral region, the photon flux from earth scenes will typically fill the unit cell charge storage capacitor in just a fraction of the frame time, limiting the full signal averaging advantage of staring technology. Even so, the improvement LWIR scanned sensors is significant.

The quality of HgCdTe photodiodes—measured by the R_0A product or by leakage current—has improved steadily over the past twenty years as materials and device processing science evolved. There is recognition that longer wavelength devices are typically more difficult to produce than medium or short wavelength diodes. A decade ago the technology was established to begin production of tactical long wavelength ($10\ \mu\text{m}$) arrays with R_0A products on the order of $10\text{-to-}100\ \Omega\text{cm}^2$. Today such devices are routinely produced with very high yield. Diode performance representative of average array quality for a spectrum of HgCdTe alloys is illustrated in typical applications. Work is still underway to push the performance of long wavelength detectors— $14\ \mu\text{m}$ and greater—to higher levels for critical applications such as monitoring the earth's atmosphere from spacecraft. In parallel with these efforts, a third generation of HgCdTe devices has emerged as described in the following section.

Third generation HgCdTe Devices

Third-generation devices are dual band, large number of pixels and advanced signal processing on chip. The technical developments which are key to third-generation devices include dry etching, vapor-phase epitaxy, optical coatings, and advanced readout concepts.

The virtues of color vision are easily appreciated in the visible because color is a powerful discriminator of everyday objects. For infrared systems, sensitivity in dual spectral bands has been demonstrated to have similar virtues.

Dual band sensors have been demonstrated using two focal planes and a beam splitter. This works, but there is considerable difficulty in optical alignment to a precision such that the exact same image feature can be accurately compared on the two focal planes at the pixel level. It also has the drawbacks of dual vacuum enclosures and cooling systems.

Two color detectors are a remarkable solution to the problem of pixel registration in dual band sensors. Two-color detectors are made with a stack of two detector layers separated by a common electrode, in the case of HgCdTe, a p-type layer. Figure 6 illustrates the structure. The Band 1 and Band 2 alloy compositions can be any two x-values as long as Band 1 has a higher x-value than Band 2. Although this structure can be grown by LPE methods, vapor phase growth is the preferred method. There are two variations of the two-color detector structure. The first type, the sequential two-color detector, has just one indium bump per pixel. Each band is read in turn by reverse biasing the diode from which the signal is desired. The device structure appears as a floating-base npn transistor, and care must be taken to avoid bipolar gain due to injection into the base.

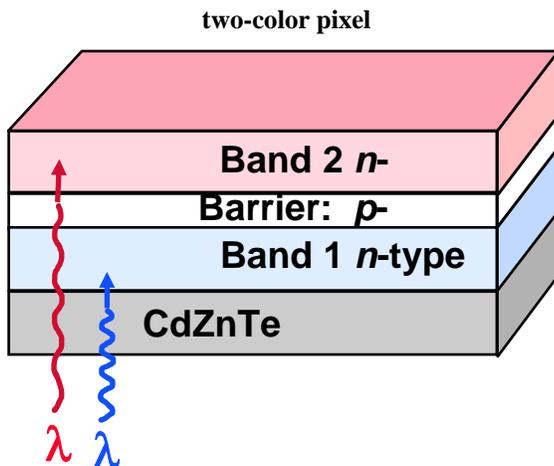


Fig 6

In addition to the importance of vapor-phase epitaxy in growing the three-layer HgCdTe structure for two-color detectors, the development of

anisotropic dry etching was important in being able to make these devices in smaller pixel sizes. This is because the mesa etch of a two-color detector is relatively deep—on the order of $12\ \mu\text{m}$ —as may be seen in Fig.7. Without anisotropic etching, much of the mesa would be consumed in isolating adjacent pixels.

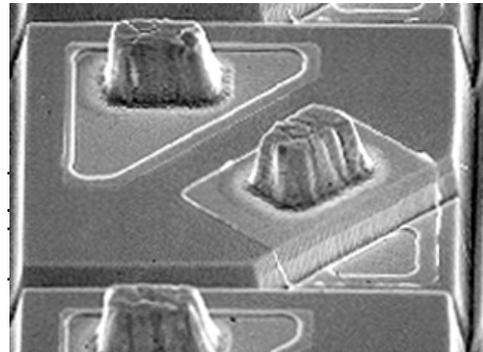


Fig 7

Conclusions

The image intensifier has evolved from Gen 0 with unity electron gain that required active illumination and a 16 KV operating voltage, to a Gen 3 version with 80,000 luminance gain that operates at 4 KV or lower component voltages.

HgCdTe has emerged as the most widely used infrared detector today because of its excellent properties, including:

- The alloy composition can be optimized for any wavelength in the range of $0.7\text{-}20\ \mu\text{m}$
- Quantum efficiency is very high
- Minimal cooling is required because the detection mechanism relies photoexcitation across an intrinsic bandgap
- The R_0A product (or inversely the leakage current) responds to cooling
- D^* varies with the background flux, improving as the flux is lowered from high to low background levels
- Growth technology has matured
- Compositional uniformity is excellent, even in the VLWIR region²⁶
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ACKNOWLEDGEMENTS Colleagues in Santa Barbara, ITT and elsewhere in the industry have established the breadth of capabilities summarized in this paper. Tse Tung has graciously helped review the materials on comparative growth techniques. Thanks are due to James Bangs, Jeffery Johnson, Libby Patten, and Jerry Wilson for material on two-color arrays.