Semiconductor Infrared Detectors

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The history of infrared (IR) detector development began with the initial discovery of IR radiation by Herschel in 1800 using thermometers.[1] The IR spectral region has intrigued scientists for almost two hundred years, but until recently it has been impossible to create IR sensors analogous to the human eye. Recent breakthroughs have come about through the creation of large 2-D solid-state arrays that have millions of detectors distributed across the focal plane of an optical system. The days of scanning-type optical systems are numbered as such systems give way to staring-type sensors. The increased sensitivity and resolution in the system complexity of focal plane arrays (FPAs) offer significant advantages in military as well as civilian applications in thermal imaging, guidance, reconnaissance, surveillance, ranging, and communication systems.

Progress in IR detector technology is mainly connected with semiconductor IR detectors, which are included in the class of photon detectors. In this class of detectors, the radiation is absorbed within the material by interaction with electrons bound to lattice atoms or impurity atoms or with free electrons. The observed electrical output signal results from the changed electronic energy distribution.

Depending on the nature of interaction, the class of photon detectors is further subdivided into different types. The most important types are

1. intrinsic detectors,
2. extrinsic detectors,
3. photoemissive (metal silicide Schottky barriers) detectors, and
4. quantum well detectors.

This special section on semiconductor infrared detectors is devoted to these four types of IR detectors. The authors are researchers in government, industry, and university laboratories who are striving to perfect this discipline.

The first paper by Rogalski discusses new trends in semiconductor IR technology: HgCdTe photodiodes, Schottky-barrier photoemissive devices, lead salt photodiodes, new ternary alloy systems for IR detectors (InAsSb, HgZnTe, and HgMnTe), and GaAs/AlGaAs intersubband quantum well IR photoconductors (QWIPs). Also, a comparison of the different types of detectors at the current stage of HgCdTe technological achievements is undertaken.

HgCdTe is the most important semiconductor alloy system for IR detectors in the spectral range between 1 and 25 μm. HgCdTe detectors as intrinsic photon detectors are characterized by high optical absorption coefficients and quantum efficiency and relatively low thermal generation rates compared to extrinsic detectors and silicide Schottky barriers. The operating temperature for intrinsic detectors is, therefore, higher than for other types of photon detectors. These attributes translate to flexibility and the capability to produce short-wavelength infrared (SWIR), medium-wavelength infrared (MWIR), and long-wavelength infrared (LWIR) detectors.

The next four papers concern HgCdTe IR detectors. Piotrowski, Gawron, and Djurić present a new way to improve the performance of IR detectors operated without cryogenic cooling, including optical immersion, optical resonant cavities, and suppression of thermal generation. The combination of various methods would eventually enable the achievement of near background-limited photodetection (BLIP) performance of IR detectors without cooling. Practical realization of this idea is presented by Ciupa et al. Their paper shows that MWIR HgCdTe photodiodes operated around 200 K exhibit BLIP performance when monolithic optical immersion is used. The performance of thermoelectrically cooled HgCdTe photodiodes is also analyzed. Arias et al. present the high performance of *p*-on-*n* heterostructure HgCdTe photodiodes fabricated by molecular beam epitaxy (MBE). One important advantage of the *p*-on-*n* device in comparison with *n*-on-*p* structures is that *n*-type HgCdTe carrier concentration is easy to control in the 10^{14}- to 10^{15}-cm^{-3} range using extrinsic doping;

for n-on-p devices, the control of p-type carrier concentration at these levels is difficult. Because of the lower carrier concentrations achieved in the n-type HgCdTe material, it has longer minority carrier lifetimes than in p-type base layers. Operability of a 64 × 64 LWIR hybrid FPA at greater than 97% has been achieved when operating at 77 K. The last paper on the subject of HgCdTe detectors (by Möllmann, Happ, and Herrmann) deals with $1/f$ noise characteristics of n^+-p $Hg_{0.5}Cd_{0.5}Te$ photodiodes. The results of this paper indicate coherent state quantum $1/f$ noise generated by dark current as well as photoinduced current due to mobility fluctuations.

From the late 1960s to the mid 1970s, because of production and storage problems, HgCdTe alloy detectors were in serious competition with IV-VI alloy devices (mainly PbSnTe) for developing photodiodes. PbSnTe alloys seemed easier to prepare and appeared more stable. The development of PbSnTe photodiodes was discontinued because the chalcogenides suffered two significant drawbacks. The first was a high dielectric constant that resulted in high diode capacitance and, therefore, limited frequency response. For scanning systems under development at that time, this was a serious limitation. However, for staring imaging systems under development today using 2-D arrays, this issue is not as significant. The second drawback to IV-VI compounds is their very high thermal coefficients of expansion. This limited their applicability in hybrid configurations with silicon multiplexers. Today, with the ability to grow these materials on alternative substrates such as silicon, this too would not be a fundamental limitation. The research group at the Swiss Federal Institute of Technology continues to pursue this technology and has made significant progress. Zogg et al. state the achievements in MBE growth and IR device fabrication with epitaxial lead salt layers on Si substrates. Tetyorkin et al. resume the discussion (initiated in the mid 1950s) of photoconductivity mechanisms in thin polycrystalline lead salt films. This paper confirms that the dependence of photoelectrical characteristics and the lifetime of photoexcited carriers on the crystalline size in PbSe films on glass and Si substrates may be explained by the existence of the barriers for the majority carriers at the grain boundaries.

HgCdTe alloys seem to be unchallenged as the most important material for IR detectors and arrays. HgCdTe has, however, the most serious technological problems of any semiconductor material in mass production. The material is difficult to grow, and devices are expensive and power-consumptive. In spite of the achievements in material and device quality, difficulties still exist due to lattice, surface, and interface instabilities. The difficulties with this material have made it desirable to examine other material systems to see whether performance can be improved. In semiconductor IR detector technologies, which have recently progressed considerably, we can distinguish PtSi Schottky barrier detectors and GaAs/AlGaAs QWIPs.

A very significant paper is presented by Yagi et al. on an improved 512 × 512 PtSi element charge sweep device imaging system. This imager, having 26- × 20-μm pixels, is fabricated with a 1.2-μm design rule and a fill factor of 71%; the experimentally demonstrated maximum charge is 2.9×10^6 electrons/pixel, and the noise equivalent temperature is 0.033 K for $f/1.2$ optics.

The next three papers are devoted to multiple quantum well IR photoconductors. The important strengths of GaAs/AlGaAs and SiGe/Si QWIPs are highly advanced material systems and the capability to rapidly fabricate new designs by programming the MBE system. Liu presents the current status of GaAs/AlGaAs QWIPs with an emphasis on multicolor and high-speed capabilities for special applications. Karunasiri et al. review the intersubband transitions in SiGe/Si quantum well structures. They also describe progress in applications of SiGe/Si multiple quantum well structures for the fabrication of IR detectors in both the 2- to 5- and 8- to 12-μm ranges. Rogalski and Jóźwikowski have carried out comparative investigations of the performance of GaAs/AlGaAs QWIPs with HgCdTe photodiodes operated at temperatures below 77 K in the LWIR region. It is shown that the GaAs/AlGaAs QWIPs can find strategic applications, taking in to account that at 40 K in the spectral range 8 to 10 μm, the detectivity of QWIPs is comparable to the best HgCdTe photodiodes, and the uniformity of quantum well detector arrays is higher.

The issue of extrinsic detectors is covered by two papers. Fouks et al. present the results of experimental and theoretical study of the spreading of a time-dependent photocurrent on the operation of low-background IR extrinsic Si:Ga photoconductor linear arrays. Wolf reviews achievements in low-background far-IR detector and array technology based on doped silicon and germanium. These photoconductors are used for IR astronomy from ground-based, balloon, and airborne observatories and from space platforms. It is expected that the problems of far-IR projects might be solved by blocked-impurity-band detectors.

The last paper by Nowak is devoted to the distribution of radiation intensity in various semiconductor film structures. The presented formulas are useful for optimization of semiconductor IR detectors to improve quantum efficiency.

It should be noted that the current privileged position of semiconductor IR detectors could change in the future. Current uncooled and near-room-temperature semiconductor IR detectors are essentially sub-BLIP detectors. Cooling requirements add considerably to the cost, bulk, weight, power consumption, and inconvenience of IR systems. In contrast, uncooled detectors are lightweight, small in size, and convenient to use. Currently, IR semiconductor imagers use cryogenic or thermoelectric coolers, complex IR optics, and expensive sensor materials. Typically, cryogenically cooled imagers cost around $100,000, which restricts their installation to critical military applications. The longer term picture, however, could change dramatically as a result of current research activities in low-cost uncooled imaging systems fabricated with thermal detectors, such as silicon bolometers or pyroelectric detectors.[2] Thermal detectors have been used little in scanned imagers because of their slow response. However, they are currently of considerable interest for 2-D electronically addressed arrays where the bandwidth is low and the ability of thermal devices to integrate for a frame time is an advantage. The 240 × 336 arrays of 50-μm microbolometers are fabricated complete with monolithic readout circuits integrated into the underlying silicon. An average NEΔT of better than 0.05 K was demonstrated with a Honeywell uncooled imager fitted with $f/1$ optics.[3] It is expected that high-performance imager system costs will be reduced by about two orders of magnitude, to less than $1000, and these types of IR cameras will become widely available in the next decade.

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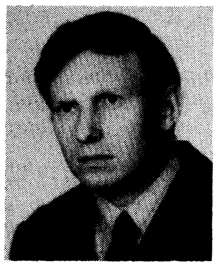

Antoni Rogalski studied physics at the Military University of Technology in Warsaw, where he received an MSc in technical physics in 1972. He received a doctor of science degree in the study of physical properties and applications of PbSnTe in 1976, also from the Military University of Technology. After this he participated in the research and design of intrinsic IR detectors such as lead salts, HgCdTe, and alternative alloy systems such as HgZnTe, HgMnTe, InAsSb, and quantum well IR photodetectors. His current fields of major interest are applied research in HgCdTe detectors, particularly photodiodes and SPRITE detectors. He is currently head of the Institute of Technical Physics of the Military University of Technology. He has authored and coauthored about 90 papers, four monographs [including "Intrinsic Infrared Detectors" published in *Progress in Quantum Electronics*, Vol. 12, pp. 87–289 (1988)] and three books [including *Semiconductor Infrared Detectors*, Milestone Series, SPIE Optical Engineering Press (1992)].