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by

Yu Xin





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# INFRARED THERMAL IMAGING TECHNIQUE: ADVANCES AND PROSPECTS

**Yu Xin**

**(Beijing Institute of Technology, Beijing 100081)**

**Abstract:** Rapid advances have been made recently in the development and applications of infrared thermal imaging technology used primarily for military purposes. In this article, advances in infrared thermal imaging are introduced in brief, and discussion is focused on technical progress in the field of infrared focal plane arrays (IRFPA). Also, the trend for infrared thermal imaging technique to expand rapidly from purely military use to civil applications is demonstrated.

## 1. Infrared thermal imaging technology and its military applications

Infrared thermal imaging technique is essentially a wavelength conversion technique, in which infrared radiation is transformed into visible light. Infrared thermal imaging is usually split into short wave (1 - 2.5 micrometers), medium wave (3 - 5 micrometers), and long wave (8 - 14 micrometers). It uses differences in each part of its thermal radiation to capture images. In the field of military night vision reconnaissance, infrared thermal imaging technology has overcome the dependence of active infrared night vision on infrared radiation sources to shine on targets and thus easily expose themselves to the enemy, and has conquered the complete reliance of passive low-light night vision on natural light in the environment. Because of infrared thermal imaging technology, military night vision reconnaissance devices can penetrate smoke, fog, haze, snow, and other limitations, and can recognize camouflage. They are not affected by intense-light or dazzling-light interference, and can carry out long-range and all-weather reconnaissance. In addition, this technology has been widely used in early warning, infrared searching and tracking, night vision navigation, strategic and imaging missile guidance, booster stage monitoring and tracking, air-based and outer atmospheric reentry interception, mechanical and satellite remote sensing, et cetera, and has thus received a great deal of attention. In recent years, the United States, Great Britain, France and other countries have competed to research infrared thermal imaging technology, and advances have come at a rapid pace.

Infrared imaging can be divided into two types, refrigerated and room-temperature. The former includes two models, first generation scanning models and second generation infrared focal plane array models, and the latter includes two kinds, one that uses a pyroelectric television camera tube [also known as a vidicon] and one that uses a pyroelectric detector array.

## 2. First generation refrigerated infrared imaging systems

First generation infrared imaging systems are primarily composed of infrared detectors, optical-mechanical scanners, information processors, and video frequency indicators. They are characterized by the use of linear array or strip devices and optical-mechanical scanning methods for covering their fields of vision. Infrared detectors mainly use cadmium mercury telluride (CMT) and indium antimonide (InSb) devices. A detector being widely developed at present is the high-performance multiple element CMT detector. This device has a high level of detection sensitivity and a high signal-to-noise ratio, and can operate in the two atmospheric window wave bands of 3 - 5 micrometers and 8 - 14 micrometers. There are two main paths of development of first-generation infrared thermal imaging systems. One is the American path of development. The United States is developing a parallel-scan system with CMT multiple element linear array devices. A heavy duty thermal imaging instrument composed of 180 element devices for vehicular and airborne use has already been developed. The other path is the development in Great Britain in the early 1980s of a new infrared detector called the Sprite detector (also known as an area-scan detector), which uses several light guide CMT element strips with aspect ratios of greater than 10:1. In addition to its detection functions, signal time delay and integration can be achieved within this device, and it uses series-parallel systems. This reduces heat loading on component parts and the number of component parts' lead wires. An eight-strip Sprite detector has the performance of a 120 element CMT, but only needs eight signal channels. The structure of its Dewar vessel is simple, its system is simplified, and its reliability is increased. The temperature resolving power of the two kinds of thermal imaging systems listed above is less than 0.1°C, and their image definition can be compared to images that use image enhancement technology. In developed Western capitalist countries, armed forces have been equipped with individual, vehicular, and airborne thermal imaging instruments that use first generation thermal imaging systems, and armed forces have successfully applied them in actual combat.

## 3. Second generation refrigerated infrared thermal imaging systems - infrared focal plane array systems

Second generation thermal imaging systems are required to have performance that is superior to that of first generation systems. They are required to have higher responsiveness, a greater number of array elements for higher resolution, no optical-mechanical scanning part, fewer lead wires, smaller size, lighter weight, good reliability, smaller energy consumption, and low cost, to meet all the higher demands of military applications. The core technology of second generation infrared thermal imaging systems is the application of an infrared focal plane array (IRFPA) detector located on the optical system focal plane.

### A. A summary of IRFPA devices

Infrared focal plane array is a new generation infrared detecting device that was formally proposed internationally in the latter part of the 1970s and has the two functions of radiation sensitivity and signal processing. Integrated circuitry methods allow thousands upon thousands of photosensitive elements to be installed in a plane array pattern on a single computer chip. Through interconnection technology, these elements connect with signal processing circuits in the same device which can directly lead out the signals produced by the sensitive elements. This greatly lessens the high-technology requirement for a large quantity of photosensitive element preparatory lead wires. Infrared focal plane array devices can fulfill all the demands for second generation infrared thermal imaging systems. They use a non-scanning method to instantly capture an image of the total field of view, and bring inestimable benefits to applied systems.

In recent years, in the field of infrared plane array device research, basic methods of constructing hybrid and monolithic focal planes have been established, and a great deal of fruitful work has been done in the fields of sensitive arrays, signal processing circuits, and interconnection technology. In the area of sensitive radiation detection device arrays, the infrared detection materials that have been fully developed over many years are still the best choices for focal planes. For example: in the short wave range from 1 to 2.5 micrometers, the best choices are palladium silicide and cadmium mercury telluride (150 to 200°K); in the medium wave range from 3 to 5 micrometers, the best choices are platinum silicide, cadmium mercury telluride (77°K), indium telluride, and indium silicide; in the long wave range from 3 to 14 micrometers, the best choice is cadmium mercury telluride (77 and 40°K); in the even longer wave range (greater than 14 micrometers), the best choices are gallium silicide (20°K), and arsenic silicide (10°K). In the area of signal processing circuitry, it is generally recognized that silicon integrated circuit technology is the only practical method for focal plane signal processing circuits. Of the two methods of constructing focal planes, more attention has been paid to the hybrid method, because it can employ material and device technologies that have advantages in the areas of sensitivity and signal processing or are relatively well-developed. When a breakthrough is made in interconnection technology, such as with cadmium mercury telluride, it is possible to manufacture a successful focal plane device. Ideal results have been achieved using an indium bump method together with silicon processing technology.

B. Technological advances in and appraisals of infrared focal plane array devices

Infrared focal plane array devices are a core technique of advanced weapon systems that use high technology. The United States, Great Britain, France, Germany, Japan, and other countries have recently used cadmium mercury telluride, indium telluride, platinum silicide, gallium indium arsenide (among other materials), and pyroelectricity to develop many kinds of infrared focal plane array devices that operate separately on the short, medium, and long wave parts of the infrared band. They have demonstrated and applied this technology in antitank missiles, antihelicopter missiles, early warning systems, infrared searching and tracking systems, air-based and outer atmospheric reentry interception systems, airborne infrared imaging spectroscopes, earth reconnaissance satellites, et cetera.

Typical technical advances include: in the field of the manufacture of monolithic silicate Schottky barrier devices, in 1988, the United States' David Sarnoff Research Center (DRC), Mitsubishi, and other corporations produced in succession 512 X 512, 640 X 480, and other standard staring PtSi SB infrared focal plane devices, and also developed corresponding pickup cameras. Recently, many commercial PtSi SB infrared thermal imaging instruments have come out. Although the quantum efficiency of PtSi devices is very low (usually less than two percent), they use standard super large-scale integration technology and have the potential for high density and low cost device preparation. The cost of PtSi devices is only several tenths of the cost of similar HgCdTe or InSb devices. Therefore, in applications where there is a low demand for performance but a high demand for space resolving power, PtSi devices are extremely attractive. The InSb CID [Charge-Injection Device] was invented in 1973 by the GE corporation. It is based on MIS [Metal-Insulator-Semiconductor] capacitors, normal position sensitivity, charge packet storage, and a monolithic medium wave device that uses X-Y addressing readout. In the mid-1980s, a technical breakthrough was achieved in InSb CID. It has 256 X 256 staring plane array imaging elements, and is at present second to PtSi devices as a well-developed, high-efficiency, low-cost medium wave infrared focal plane array. In the area of hybrid focal plane array research, HgCdTe devices are representative. Because their components can be adjusted, they can affect short, medium, and long wavelengths, have high quantum efficiency, long optical lives, a high absorption coefficient, and a relatively high operating temperature, they receive the greatest amount of attention from researchers, and, up to now, have been the only practical way of achieving 8 to 14 micrometer wavelength infrared focal plane devices; however, they have a high degree of preparation technology difficulty. The United States' Rockwell company, using PACE-I, liquid-phase epitaxy, indium bump interconnection, and other technology, has produced a short- and medium-wave 256 X 256 element HgCdTe PB/silicon CCD [Charge-Coupled Device] hybrid infrared focal plane array with a refrigeration temperature of 80°K, a duty ratio of 99%, a quantum efficiency of 61%, and good performance. Another high-performance medium wave focal plane device that has shown up prominently in recent years is the InSb array. The United States' Amber Engineering company has manufactured the AE4256, a 256 X 256 element InSb PV/Si CCD hybrid array. This device's average quantum efficiency is approximately 53%, and its average detection $D^*$ is $7.56 \times 10^{11} cm^2 \cdot hertz^{1/2}/watt$. This device was used in the Persian Gulf War. The primary long wave focal plane array device is the long wave HgCdTe device. Because its substrate material technology is not mature enough, preparation is more difficult. The American company Texas Instruments has recently invented a method that does not require light to pass through the substrate to the array, called the vertical metal-insulator-semiconductor method. A 64 X 64 element long wave HgCdTe staring focal plane array has been achieved and applied in an experimental demonstration of a U.S. Army advanced (medium) antitank weapon; 128 X 128 element and larger staring focal plane arrays are also under development.

From the above, it is clear that infrared focal plane array technology has experienced marked overall development and has entered the realm of practicality. From the viewpoint of the needs of military systems, if the number of imaging elements on focal plane arrays can reach 128 X 128 (or 256 X 256), many present first generation infrared scanning thermal imaging instruments can be replaced with second generation staring systems. Future tactical applications demand an imaging element number of greater than 512 X 512. For the Strategic Defense Initiative's outer space monitoring and defense systems, satellite remote sensing, and strategic weapons, the number of imaging elements must be greater than $10^7$. We can say that the technological level of short and medium wave infrared focal plane array devices has reached a completed or almost completed experimental development level of tactical system applications, and these devices are in transition towards mass production. Long wave infrared focal plane array device technology, especially for large devices with more than 256 X 256 elements, still requires thorough study and development. For strategic applications of short, medium, and long wave technology, it is necessary to continue carrying out thorough research and tackle key problems.

**4. Room-temperature infrared thermal imaging systems**

The above infrared thermal imaging systems are all refrigerated systems. They are heavy and bulky, consume a lot of energy, have a high degree of technical difficulty, and their cost is too high. Therefore, recently, a kind of room temperature infrared thermal imaging system has been developed. Room temperature infrared imaging technology employs pyroelectric detectors to detect thermal radiation from objects and their backgrounds. This technology uses the characteristic of sensitivity of pyroelectric detectors to temperature changes caused by infrared rays to create images through photothermoelectrics and photo-electric conversion. These changes in temperature are directly proportional to some of the detectors' parameters, such as pyroelectric currents.[1] These systems' main advantage is that they can operate in most environmental temperatures without refrigeration; their drawbacks are that they have low sensitivity, slow responsiveness, and their performance is inferior to that of photon detectors. At present,

[1] The latter three sentences were made from one long Chinese sentence that lacks a main verb. Text may have been missing.

room temperature thermal imaging systems primarily use two kinds of detectors. One uses pyroelectric television camera tubes manufactured from triglycine sulfate (TGS) and other materials. Its temperature resolving power is less than 0.2°C. The other uses a hybrid structure made up of multielement focal plane array pyroelectric detection devices and solid-state multichannel electronic transmission devices. Its responsiveness and resolving power have already reached the levels of first generation refrigerated infrared imaging systems. Because this kind of system can operate at room temperature, it neither requires Dewar vessels, high-pressure gas bottles, nor other cooling systems, nor does it require optical-mechanical scanning devices. Thus, it can be much lighter in weight, expend much less energy, its cost can be reduced, and it can be much more reliable. For example, the capacitance of the room-temperature operational 80,000 element array barium titanate pyroelectric detector developed by Texas Instruments varies with the temperature. A large number of microdetectors constructed on a ferroelectric material basis form an array and are installed on an insulating plinth. Microcircuits provide a noise equivalent temperature differential (NETD) of less than 0.1°C. This detector uses a liquid crystal display, weighs only 1.35 kilograms, and is portable. Clearly, in situations where medium sensitivity and medium responsiveness are demanded, the prospects for applications of room temperature thermal imaging technology are very attractive.

## 5. Civilian applications are rapidly opening up

The development trends of military infrared imagery technology are as follows: for first generation infrared imaging systems, carrying out a module interchangeability plan; for second generation systems, organizing industrialized production, lowering costs, and raising the finished product rate of short and medium wave infrared focal plane array devices, accelerating the development of long wave infrared focal plane array devices, researching array module integration technology, realizing large-scale integration of infrared focal plane arrays, and researching infrared focal plane arrays that employ principles of superconduction. At the same time, developed capitalist countries are accelerating the opening up of civil applications for infrared imaging technology; this is a noteworthy development trend.

In the field of industry, infrared thermal imaging technology has primarily been applied to production process monitoring and non-destructive materials inspection. For example, it is used in production line monitoring of steel, aluminum, paper, foods, glass, and plastics, as well as keeping watch over rotating lime and cement kilns, car windshield glass manufacturing, and robot welding. Because of its non-touching, telemetric nature and ability to carry out high-sensitivity total-field monitoring, it has received widespread usage in these areas. In the foreseeable future, it will have a great significance in transforming the entire production process and raising production rates and product quality. In the medical field, infrared imaging technology has found applications in diagnosis of illness. Infrared imaging technology has also been applied to police work, private security, electric power systems, traffic monitoring, remote sensing, disaster monitoring, and other situations. It can be said that full play can be given to infrared imaging technology in all applications and fields that previously used "some" infrared detectors.

As the level of development and production of infrared focal plane array devices has risen and, even more, because the former Soviet Union collapsed, the cold war between the United States and the Soviet Union has ended, and military orders for goods have greatly decreased, companies that develop infrared thermal imaging systems in America, Japan, and other countries have invested large amounts of human and material resources in competing to be the first to bring out infrared imaging systems for civil use and open up the civilian market. In 1988, Mitsubishi Electrics was the first company to bring to market an infrared focal plane array thermal imaging system, the IR5120. At the time, its current price was U.S. $100,000, it weighed 20 pounds, and it required an electric power supply. Over the past five years, civilian infrared thermal imaging technology has advanced a great deal, and there are now at least eight companies that sell infrared thermal imaging systems. At the SPIE [Society of Photo-Optical Instrumentation Engineers]

15th Thermal Detection Science Conference held in April 1993, Poland's FLIR [Forward Looking Infrared Radar] Group displayed a 244 X 320 element PtSi infrared focal plane array thermal imaging system. Inframetrics of Billerica displayed the smallest and lightest hand-held infrared focal plane thermal imaging system at the time. Its detector was a 256 X 256 PtSi, it weighed only three pounds, and it used a micro-cooler that just needed three watts to operate and could work off batteries. Its price was between U.S. $35,000 and $40,000. The Amber company provided a 256 X 256 element portable InSb infrared focal plane array system called Radiancel, and plans to bring out an HgCdTe system in the near future. The Santa Barbara Focal Plane division of the Westinghouse company announced that it could provide a 128 X 128 element GaAs quantum well infrared focal plane array whose response range is between 7 and 11 micrometers and whose peak value response is 9 micrometers.

Efforts to bring infrared focal plane array technology to the civilian market are mainly focused towards making systems lighter in weight, developing hand-held systems, lowering costs, and making systems more user-friendly. Technological advances include the Stirling circulating cooler and the Peltier pyroelectric cooler that employ electric micro-refrigeration. These coolers have a cooling temperature of 77°K, require only three watts of power, and will make the cumbersome refrigeration methods that use gas bottles or liquid nitrogen to operate obsolete. Signal processing has greater storage capacity and can store hundreds of times as much digital image data, and has integrated many kinds of image diagnosis and processing functions. To lower the cost of focal plane arrays from several tens of thousands of U.S. dollars to the target cost of several thousands of dollars, production bases will be established and investment will be made in large-scale production.

There are broad prospects for civilian applications of infrared thermal imaging technology. During the 1990s, gross demand for infrared focal plane systems will reach 300,000 units. To accelerate the achievement of the four modernizations, China should also forcefully promote and develop civil infrared imaging technology.

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