Thermoelectric Applications for Imaging Infrared Focal Plane Arrays

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The development of thermoelectric (TE) materials and device structures is essential to the performance of many commercial and military electronic systems. Tactical infrared (IR) imaging sensors, for example, typically require some form of cooling to optimize performance and range without compromising on size, weight and power. The dark current for these imaging sensors increases with wavelength thus adding to the cooling requirement. Novel approaches are being developed to integrate low dimensional materials that exhibit enhanced TE properties with IR focal plane array (FPA) manufacturing processes. These types of approaches could significantly increase the potential of future fielded soldier imaging systems.

1. Introduction

Thermoelectric devices are becoming more convenient and necessary for many military and commercial cooling applications. Solid-state semiconductor thermoelectric coolers (TECs) provide numerous advantages over conventional refrigerant based cooling systems given that they are compact, quiet, rugged and reliable without containing any ozone damaging chlorofluorocarbons. TECs have modest efficiency in relation to compressor based refrigerators but can be utilized effectively for niche applications. Many military TE cooling uses are common to commercial applications such as electronic component cooling for integrated circuits. Other military applications include reliable TE air conditioners for sensitive equipment enclosures, soldier cooling systems as well as cooling components for imaging devices.

The efficiency of TECs has a direct impact on the variety of applications for military imaging systems that cover visible, near infrared (NIR), shortwave infrared, (SWIR), midwave infrared (MWIR) and longwave infrared (LWIR) spectral bands. These electro-optical and infrared devices are more commonly being integrated on air, ground and soldier platforms. Furthermore, low light level and long range imaging systems are critical for detection, recognition and identification of potential threat targets. High performance imagers typically require some form of detector cooling mechanism that is lightweight, low power with a small form factor. These infrared focal plane arrays (FPAs) benefit from cooling to help mitigate dark current in order to boost the signal to noise ratio (SNR) thus increasing performance and effective standoff range. Even un-cooled infrared technologies benefit from temperature stabilization in order to perform a non-uniformity correction (NUC) to normalize the offset and/or gain on a per pixel basis. Single and multi-stage TE devices are preferred over dewars that require liquid cryogens or closed cycle cryo-coolers which are large, heavy and may induce excess vibration and electronic noise. DARPA's High Operating Temperature Mid-Wave Infrared (HOTMWIR) Program is currently focused on MWIR technologies such as HgCdTe that may operate at -20°C and eliminate the need for a cryo-cooler. The same case can be made for HgCdTe LWIR potentially operating at -50°C.

2. Infrared Imaging Applications

Infrared FPA technologies stand to benefit greatly from emerging thermoelectric research in the area of novel TE nano-materials. Low dimensional structures, such as quantum wells, super-lattices, quantum wires and quantum dots may be engineered to provide enhanced thermoelectric properties. The quantum confinement effects of these low dimensional materials can be used to achieve high thermoelectric figure of merit by controlling the energy distribution of electrons and phonons independently [1-6].

The thrust forward will be to integrate the construction of a highly efficient thermoelectric device with that of an infrared focal plane array thus providing effective cooling directly to each individual pixel. Polymer based or monolithically grown TE materials could potentially be incorporated into the focal plane array fabrication processes of the detector material or monolithically integrated with the readout integrated circuit (ROIC). HgCdTe infrared devices, for example, have been successfully grown directly on $Hg_xCd_{1-x}Te/Hg_yCd_{1-y}Te$ super-lattice TE coolers using molecular beam epitaxy. This monolithic integration of the infrared sensor material and thermoelectric elements also significantly reduces the thermal load necessary to be cooled [7, 8].

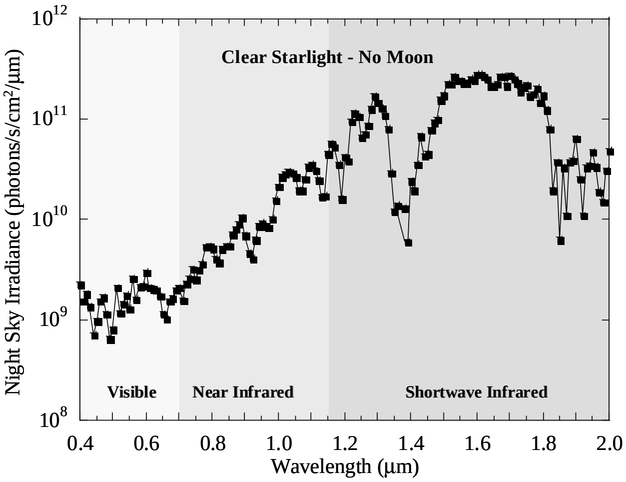

Figure 1. Ground-based measurement of clear starlight night sky irradiance (photons/s/cm^2/µm) as a function of wavelength from 0.4 – 2.0µm.

Another very promising thermoelectric application for direct integration with an infrared imaging sensor is with shortwave infrared FPAs. Development of low noise solid state detector arrays in the shortwave infrared has progressed significantly over the past decade to the point where SWIR devices are being evaluated for digital solid state low light level applications. Solid state SWIR imaging sensors benefit from natural nightglow irradiance which is over an order of magnitude greater than in the visible and near infrared wavebands combined (Figure 1). Nightglow is comprised mostly of hydroxyl ion (OH-) emissions due to vibrational and rotational transitions originating at an altitude range of 70 to 110km, producing energy in several bands contributing significantly to the night sky irradiance especially wavelengths above 1µm.

Typical passive low light level imaging sensors are generally signal to noise limited at a given night sky illumination condition ranging from fractional moon, through clear starlight, down to overcast starlight. The performance limiting factor for most of these systems is the low amount of available natural scene flux within the operational spectral band of the system and the system's efficiency to convert these low signal levels relative to its fundamental noise floor. The primary signal independent noise mechanisms in SWIR focal plane arrays are the shot noise generated by the dark current and the noise caused by the readout integrated circuit. The dark current noise (n_d) contribution to the detector noise is a function of the dark current density (j_d), detector area (A_d) and integration time (t_{int}) given by:

$$n_d = \left(\frac{j_d \cdot A_d \cdot t_{\text{int}}}{e} \right)^{1/2}$$

Shortwave infrared photodetector materials include, but are not limited to, InGaAs, HgCdTe, InSb and Germanium. The dark current density of InGaAs lattice matched with an InP substrate has been significantly reduced recently through research and development efforts and are now reaching below 7nA/cm^2 at 22°C [9]. Germanium SWIR photodetectors have also shown promise as a low cost alternative but exhibit much higher dark current and require significant cooling down to ~200K. Even though the dark current for lattice matched InGaAs is relatively low at room temperature it increases exponentially with temperature, as illustrated in Figure 2, which has negative implications for tactical applications requiring operation at ambient temperatures reaching 40 – 50°C. For example, a low light level InGaAs SWIR detector array with a 15µm pixel pitch operating at 30Hz full frame integration produces approximately 20, 56, and 150 rms noise electrons per pixel per frame at 0, 22, and 45°C, respectively. In order to achieve true photon counting cooling the array must be performed. Unfortunately, even cooling using conventional TE modules requires a few Watts (Figure 3) which places a strain on the power budget for potential fielded soldier systems.

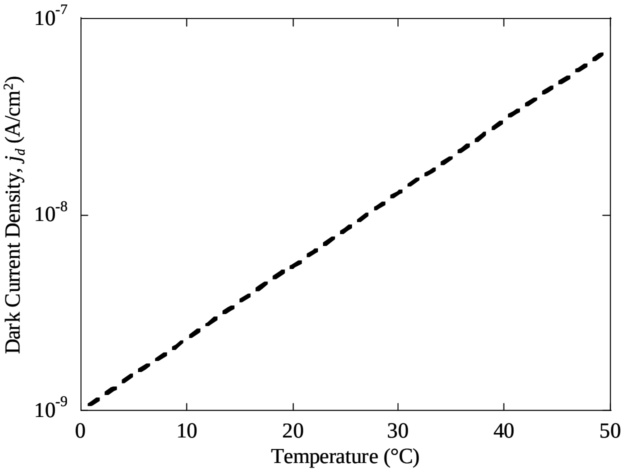

Figure 2. Representative dark current density (A/cm^2) for lattice matched InGaAs SWIR photodiodes as a function of temperature [9].

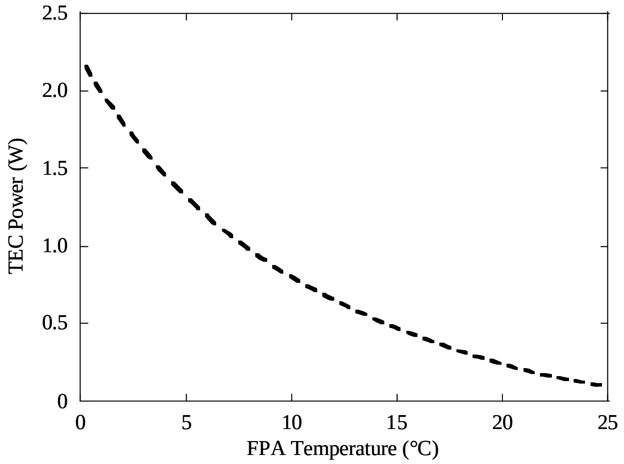

Figure 3. Thermoelectric cooler power (W) for an InGaAs SWIR FPA as a function of FPA temperature with an ambient of 25°C [9].

Recently, Princeton Lightwave Inc. (PLI) and Nextreme Thermal Solutions Inc. have announced an agreement to jointly develop an integrated TE cooled SWIR FPA that may provide a significant advantage over traditional TECs. The approach is to incorporate Indium Gallium Arsenide (InGaAs) focal plane arrays from PLI with Nextreme's thermal bump technology to considerably reduce weight and power consumption. The thermal copper pillar technology uses TE based solder bumps that are attached to the focal plane array. Each solder bump is made up of a nano-scale thermoelectric thin film that transfers heat from each pixel to the copper pillars that carry heat from the sensor [10].

Conclusions

Thermoelectric devices remain important to military electronic component cooling where such applications generate an estimated billion dollar a year market. Innovative low dimensional materials are currently being investigated that exhibit enhanced TE properties while newly developed integration techniques are also being explored to incorporate thermoelectric materials with IR focal plane array manufacturing processes. The success of these approaches are expected to greatly reduce the size, weight, and power of the traditional TECs currently required for non uniformity corrections and dark current mitigation of thermal and passive low light level infrared imaging sensors.

Notes and References

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