A New Approach for Quantum Infrared Detection at Room Temperature

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ABSTRACT

Performance of quantum LWIR/MWIR photo-detectors is limited by dark-thermal current. Common approach is to reduce the thermal current by cooling the devices to cryogenic temperatures, preventing dark-thermal excitation of carriers disturbing the IR detection process. Sirica presents a new approach enabling quantum IR detection at room temperature. Instead of cooling the device, the free carriers are heated. Once their temperature is much higher than that of the device material lattice, heat transfer from the cold lattice to the hot free carriers is not possible due to thermodynamic laws. Heat transfer from hot carriers to the lattice is prevented by selecting a media where free carriers remain hot for long enough time (longer than their expected recombination lifetime). Thus, the device material lattice and hot free carriers are thermodynamically uncoupled and the device appears “cool” at room temperature. The hot carriers are then excited by IR photons to generate electron–hole pairs which are further converted to visible or NIR photons detectable by commercial visible CMOS/CCD sensors, a process known as “energy up-conversion”. The energy required for up conversion is provided by an external low power light source. The new media required for effective light conversion is made of all silicon-based materials and offers the following benefits: (a) essentially non-equilibrium free carriers; (b) strong free carrier absorption of IR radiation; and (c) effective visible/near IR luminescence originating from the IR excited carriers. The theoretical model underlying the device and experimental results showing photo-induced free carrier IR absorption and IR-induced photoluminescence are presented.

Keyword list

Uncooled; Photon; IR detector; Energy up-conversion, Silicon

1. INTRODUCTION

1.1 IR detectors - present status

Modern IR detectors capable of sensing IR radiation in the two atmospheric windows – middle wavelengths 3-5μm (MWIR) and long wavelengths 8-14μm (LWIR) - are largely divided into two categories based on the principles of their operation, known as thermal and photon (quantum) detectors. Each of the above categories contains several sub-categories that vary in their material composition, operating mechanism, operating requirements and performance.

Thermal IR detectors (uncooled) (thermopiles, bolometers and pyroelectric) – operate in a two-step process: (a) the absorption of the IR radiation changes the device’s temperature (i.e. signal depends on radiant power rather than on wavelength/spectral contents); and (b) the change in device temperature changes some other parameter in the device (e.g. voltage, resistance, electrical polarization) that is then converted to an electrical signal. Their main advantages are in the avoidance of cryogenic cooling requirements and in a relatively simple manufacturing process. Hence these detectors are lightweight and compact, with low power consumption. Their prices are in the range of few $K’s - substantially lower than quantum detectors. Their main disadvantages are expressed in their limited performance capabilities and in the necessity for vacuum packaging. Slow response (milliseconds) and moderate detectivity (1/100 of cooled photon detectors) limit their use to moderate performance applications. The requirement for high cost vacuum packaging, providing thermal isolation of the sensitive elements required for appropriate detectivity, is the main barrier preventing thermal detectors from becoming a candidate for low cost detector, mass production commercial and military applications.

Photon (quantum) IR detectors (intrinsic, extrinsic, photoemissive, and quantum structures-such as quantum-well (QWIP) and quantum-dot QDIP) – generate an output signal that is proportional to the number of photons absorbed in the device material rather than to their total energy. At the same time the energy of each single photon must be high enough to cause delocalization of carriers across the device structure, resulting in increasing the device conductivity (as in photoconductive detectors) or in generating potential difference across a junction (as in photovoltaic detectors). These detectors are characterized by selective energy (or, wavelength)-dependent response. Their main advantages are in improved performance (mostly fast response time and excellent signal-to-noise ratio). However, to achieve this performance in the MWIR and LWIR they require cryogenic cooling in order to reduce thermal noise by preventing thermal generation of free carriers that would compete with the optically-generated carriers. Consequently, photon detectors are characterized by their high cost, high power consumption, heavy weight, large size and continuous maintenance requirements.

The best photon detectors are intrinsic, i.e. based on narrow bandgap semiconductors requiring complicated growth techniques. These materials are relatively soft with a low damage threshold. Hence, their manufacturing involves tricky and delicate processes that impose serious yield limitations on increasing the number of elements in the 2-D scanned arrays. The most widely used material is a compound of Mercury (Hg), Cadmium (Cd) and Tellurium (Te) – MCT, demonstrating excellent quantum efficiency (>70%), and bandgap that can be tunable to the desired wavelength by altering the compound structure composition. MCT detectors require cooling to about 77^oK for LWIR, and about 120^oK for MWIR. Another common detector, used for IR detection in the MWIR spectrum, is made of indium antimonide (InSb). Being a true stoichiometric compound, this detector produces highly uniform response, but still requires cooling to 80^oK.

Current versions of photon IR detectors provide superior performance, which is essential for high-end applications, where performance requirements cannot be compromised. However, the combination of manufacturing difficulties and cooling requirements make these detectors very costly (in the range of few $10'sK) and bulky, and as a result the commercial applications for this technology are limited.

1.2 Summary of the current state of the art

The enormous potential value of thermal imaging and other IR detector applications have been stimulating intensive research over the past several years. Many advances have been achieved, some of which are already translated to commercial products, and some of which are still in development at research laboratories. Improvements in thermal IR detectors were accomplished relatively recently with the development of microbolometers, and in photon IR detectors with the development of the QWIP and, more recently, QDIP photon detectors. However, all photon detectors still require cooling to cryogenic temperatures, which limits their usage due to size, weight and cost. On the other hand, the performance of uncooled microbolometers limits their use to medium and low end applications. The vacuum packaging technology required to operate them represents a cost barrier that prevents the technology from being a true 'enabler' of low cost, mass market applications in commercial and military markets. The industry is still waiting for the big breakthrough technology that will offer the combination of *superior performance at affordable cost for the high end applications,* ***and*** *solid performance at very low cost for mass market applications*. Such a breakthrough is likely to incite an infrared revolution that could be felt by everyone.

1.3 Sirica's innovative approach to IR detection

Silicon-based visible-light detectors are widely available for numerous commercial applications (e.g. digital still and video cameras) and are therefore very inexpensive; however, they are not suitable for detection of IR radiation. Using these low cost silicon detectors (and electronics) for IR night vision would be possible if there existed an ability to convert LWIR or MWIR radiation into visible or near IR light. Once such a conversion can be achieved, IR night vision could be almost as price competitive as visible imaging (IR cameras for the price of digital cameras).

Sirica is developing a novel, simple deposition-based technique, fully compatible with silicon CMOS process, for the production of a whole-optical, photon but uncooled, infrared-to-visible light converter, to be integrated with silicon-based CMOS/CCD image sensors and their system on chip electronics for the manufacturing of the ultimate, "detector-on-a-chip" IR detector.

2. PRINCIPLES UNDERLYING SIRICA'S TECHNOLOGY

The operating mechanism of Sirica's uncooled photon IR detector is based on the up-conversion of photon energy, i.e. conversion of low-energy IR photons to high-energy visible or NIR light, that, can be detected by standard Si CCD/CMOS image sensors. An external pumping light source is used to provide the additional energy required for up-conversion. Such conversion occurs in a proprietary Si-based composite structure with optically tunable properties. In order for this conversion layer to work it is required to enable: (a) strong IR photoemission of free carriers; and (b) free carriers exhibiting strong radiative recombination in the visible or NIR spectral ranges.

2.1 Free carriers absorption of IR photons in metal-like materials

Silicon (Si) has proven itself the material of choice for visible spectral range image sensors. Conventional CCD and CMOS imagers are widely used in video and digital cameras and their enabling manufacturing/processing technologies are very mature and cost-effective. However, the natural band-gap of bulk Si (approximately 1.1eV) manifests its transparency for IR radiation at wavelengths longer than 1.1 microns. Consequently, Si is not sensitive to radiation in the MWIR and LWIR spectral ranges. Therefore, the first challenge is how to get Si to effectively absorb IR radiation and emit IR-excited free carriers.

One way of forcing silicon to absorb IR radiation is by creating a large number of free carriers in the bulk material. To get reasonable IR Free Carrier Absorption (FCA) the number of free carriers must be enormous (in the order of $\sim 10^{22} \div 10^{23} cm^{-3}$) similar to metals [1]. Essentially, the Si needs to be converted into metal-like material. IR detectors based on this principle are well known as silicide-based Schottky-barrier (photo-emissive) detectors. The best known Schottky-barrier detector is the PtSi detector, which is used for detection in the MWIR spectral range. The radiation is transmitted through a silicon substrate and is then absorbed in metal PtSi (and not in the semiconductor). The energy diagram and carriers equilibrium distribution function are demonstrated in Fig. 1.

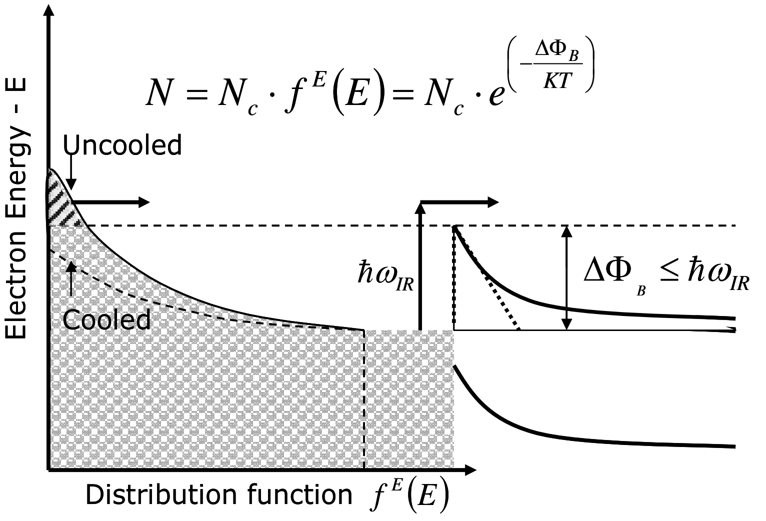

Figure 1: Energy bands diagram and free carrier *equilibrium* distribution function f^E in a Schottky-barrier photo emissive IR detector. N_c represents the concentration of free carriers in the metal/silicide electrode.

Excited by IR radiation, carriers are emitted over the potential barrier into the silicon, leaving the silicide charged. This charge is transferred to a CCD by the direct charge injection method. The main advantage of these detectors lies in the fact that they are the least expensive photon sensors, demonstrating excellent spatial uniformity (thanks to Si-based technology). Their main disadvantage is in their poor quantum efficiency (in the order of 1%), and the requirement for an operating temperature which is even lower than other IR photon detectors. In order to increase their quantum efficiency (i.e. the number of photo-emitted carriers per incident IR photon), the width of the absorbing layer must be thick enough to absorb as many IR photons as possible, but, at the same time, thickness is limited by the need of the photo-excited carriers to reach the barrier without losing energy due to strong electron-electron interactions in the silicide electrode. Carriers' excitation distance from the Schottky barrier must be shorter than the energy relaxation length (typically $d \le 10^{-5} cm$), thereby limiting the effective width of the absorbing layer, resulting in low quantum efficiency. [In comparison, the situation in MCT photovoltaic detectors is more favorable since the width of the absorbing layer is limited by the diffusion length of minority carriers (typically $\sim 10^{-3} cm$), resulting in a significantly better quantum efficiency].

Returning to the Schottky-barrier detectors, their low quantum efficiency necessitates strong suppression of thermal noise in order to obtain signal-to-noise ratio acceptable for detecting weak IR signals. This is normally achieved by cryogenic cooling of the detector. Ideally, thermal noise should be reduced below the background noise so that the performance of the IR detector would be limited by the background radiation alone - Background Limited Infrared Photodetector (BLIP).

The operating principles underlying Sirica detector are basically similar to photo-emissive detectors, but without all of the disadvantages. As in a silicide Schottky-barrier detector, Sirica's detector is also based on the Free Carrier Absorption phenomena. However, whereas the absorption of IR photons in photo-emissive detectors is achieved by equilibrium free carriers that exist in the silicide/metal electrode of Schottky diode, the free carriers in Sirica's detector are photo-induced by a low power external light source (pumping light) to form strongly non-equilibrium hot carriers with slow relaxation time to the equilibrium state (Fig. 2).

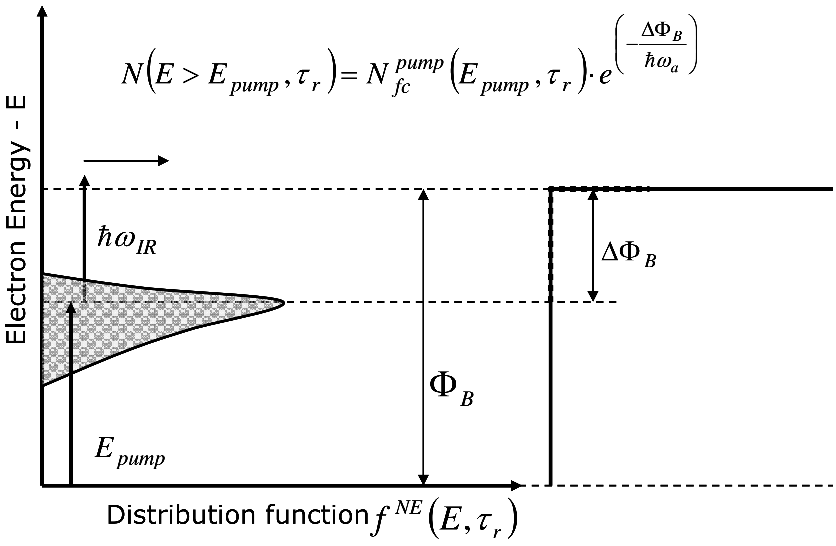

Figure 2: Energy band diagram and free carrier *non-equilibrium* distribution function in Sirica's converting composite structure. *N* represents the concentration of free carriers excited by a pumping light source with energy E_{pump} at the moment of recombination τ_r.

The composite structure is made of matrix material with embedded Si inclusions. The pumping light photon energy determines the average energy E_{pump} of the carriers' distribution. The difference $\Delta\Phi_B$ between the height of the natural barrier between the inclusions and matrix material Φ_B and the average energy of free carriers would become the barrier for IR photo-emission. Pumping light can be in the form of assemblies of surface mounting LEDs. The size of the inclusions is smaller than the momentum relaxation length of free carriers. Therefore, the motion of the hot carriers inside these inclusions is purely ballistic and their inelastic scattering would result in the excitation of surface phonons. This mechanism of energy relaxation is ineffective [2]. In this case, the recombination time of such confined free carriers may be shorter than their energy relaxation time. Experimental evidence to these phenomena were recently published [3] [4] and demonstrated in Sirica’s lab. *These hot carriers strongly absorb IR radiation and are emitted over the energy barrier on the interface between the inclusions and the matrix material where they recombine radiatively.*

2.2 Strong free carrier IR absorption and electron photo-emission in Si-based composite structures

Sirica’s composite structure demonstrates exceptionally strong free carrier IR absorption (Fig. 3). Such high values of absorption coefficients are comparable with the values typical for silicide and metals, where the number of the equilibrium free electrons is in the range of $10^{22} \div 10^{23} cm^{-3}$ (plasma frequency of same order of the IR photon frequency). However, the concentration of *non*-equilibrium free carriers capable of absorbing IR photons in Sirica’s composite structure is several orders of magnitude smaller (assuming reasonable pumping light intensities and non-equilibrium carrier lifetimes).

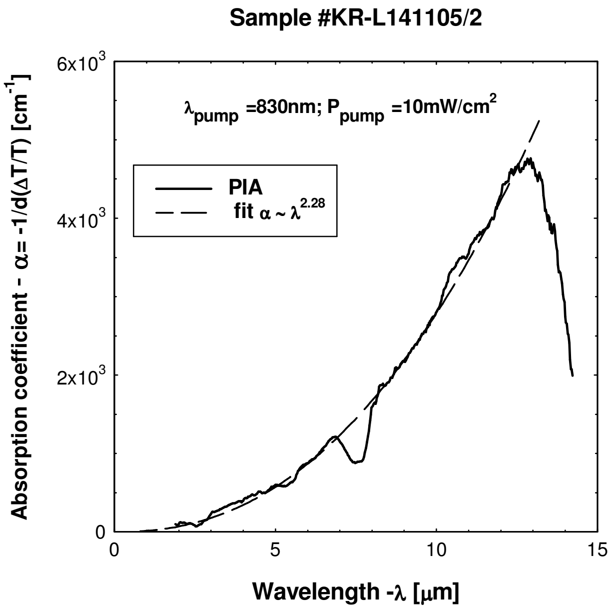

Figure 3: Absorption coefficient extracted from the measured photo-induced absorption (PIA) in Sirica's composite structure at pumping light wavelength λ_{pump} = 830nm and power density 10mW/cm^2. Curve fit with $\alpha\sim\lambda^{2.28}$ indicates free carrier absorption

Hence, a high value of absorption coefficient can only be associated with a very large cross section of IR absorption, which is possible only in the case of resonance absorption such as realized in Sirica's structure. A similar phenomenon was predicted in 1970 for 2-D composite structures [5] and in 1977 for a 3-D case [6]. Detailed reviews of experimental and theoretical results discussing resonant absorption in composite structures are also available [7] [8]. As for quantum efficiency of IR photo-emission, in Sirica's case, the emission originates from the inclusions where the concentration of the photo-induced free carriers is relatively small, and the energy loss due to electro-electron interactions is negligible. Moreover, due to the fact that the inclusions size is smaller than the momentum relaxation and the energy relaxation length, the hot carriers would reach and overcome the barrier placed on the interface between the inclusions and the matrix material without losing their energy.

Unlike the case of Schottky-barrier detectors, Sirica's whole-optical converter is a 3-D structure where IR absorption occurs in each isolated inclusion. The transport properties of the matrix are irrelevant since radiative recombination of photo-emitted carriers occurs in the vicinity of each inclusion. Therefore there are no restrictions on the thickness of the conversion layer, and high values of quantum efficiency of IR photo emission can be expected.

2.3 Converter layer thermal noise and cooling issue

In Sirica's converter layer, the hot carriers excited by the pumping light, confined within the inclusions of the composite structure, form a strong non-equilibrium distribution function (NEDF) since the pumped electrons abides by $E_{pump} >> KT$ (see Fig. 2 above). In the case of monochromatic photo-excitation, the NEDF of the free carriers in the energy space will appear strongly asymmetrical [9]. The high energy decay of the NEDF is defined mainly by the interaction of the non-equilibrium free carriers with the acoustical phonons. It can be shown that the momentum of the acoustical phonons $\hbar\vec{q}$ that contributes mostly to the scattering process is of the same order as that of the free carrier $\hbar\vec{q} \le 2m^*\vec{v}(\varepsilon)$, where m^* the effective is mass and $\vec{v}(\varepsilon)$ is the velocity of free carriers. The energy of these phonons $\hbar\omega_a(\vec{q}) \le \sqrt{2m^* c_s{}^2 E_{pump}}$ is much lower than KT for all $E_{pump} < KT\sqrt{KT/2m^* c_s^2}$, where c_s is the sound velocity in Si inclusions. Thus, in the non-equilibrium case, the number of carriers with energies higher than the barrier height $\Delta\Phi_B$ is defined by the NEDF function $N^{NE}(\varepsilon \ge \Delta\Phi_B) = N_{pumped}(E_{pump})\cdot\exp(-\Delta\Phi_B/\hbar\omega_a)$. Therefore, from the thermal noise point of view, the non-equilibrium device operating at temperature T behaves similarly to an equilibrium device working at some effective temperature $T_{ef} = T/(KT/\hbar\omega_a)$ which is significantly lower than the actual operating temperature.

Sirica's technology therefore enables a photon detector that appears cool at room temperature and can deliver performance that is background limited.

2.4 Efficient visible radiative recombination in the converter composite structure

The efficiency of radiative recombination in the converter layer η_{IRIVPL} is defined as the ratio of IR-induced free carrier non-radiative recombination lifetime τ_{nr} to the total recombination time in the matrix of composite structure $\tau_{nr} + \tau_{rr}$. In order to achieve high values of η_{IRIVPL}, radiative recombination time τ_{rr} must be significantly shorter than the non-radiative one. In Sirica's proprietary structure it is achieved by introducing into the matrix of the composite structure radiative recombination centers of densities $N_{rr} \sim 10^{16} \div 10^{17}\, cm^{-3}$ and a tremendous capture cross section $\sigma_{rr} \sim 10^{-14 \div -13}\, cm^{-3}$ (patent pending). Under τ_{rr} as short as 10^{-10} sec, radiative recombination is the most probable recombination channel in the structure. Therefore, an efficiency of close to 100% seems feasible. Preliminary experimental results proved such possibility.

2.5 Efficient up-conversion of photon energy

When speaking of conversion, the question regarding conversion efficiency is critical. Conversion efficiency is defined by the ratio $\eta_{conversion} = \Phi_{VIS} / \Phi_{IR}$, where Φ_{VIS} is the visible photon flux detectable by a silicon detector (CMOS, CCD) and Φ_{IR} is the detectable IR photon flux. Since Sirica's converter performance is background limited at room temperature, its noise equivalent IR photon flux is defined by background fluctuations. Since the background noise in the LWIR band is about 3 orders of magnitude greater than the noise of silicon detectors/imagers, it can be safely assumed that conversion efficiency of 10^{-3} should be sufficient for achieving performance similar to that of state-of-the-art MCT detectors, working at 77^{o}K. The noise of thermal detectors is defined by the thermal noise; therefore conversion efficiency of 10^{-5} should be sufficient to achieve the limited performance of state-the-art uncooled thermal detectors. As was described above, the conversion process can be divided in two steps: (a) IR emission of free carriers over the barrier; and (b) radiative recombination of these carriers in matrix material. The conversion efficiency in this case may be presented as a product of quantum efficiency of IR emission and the efficiency of the IR-induced visible photoluminescence. As discussed above, both parameters are sufficiently large. Preliminary experimental results are presented in Fig. 4. *In practice, conversion efficiency of more than* 10^{-1} *is feasible with Sirica's technology.*

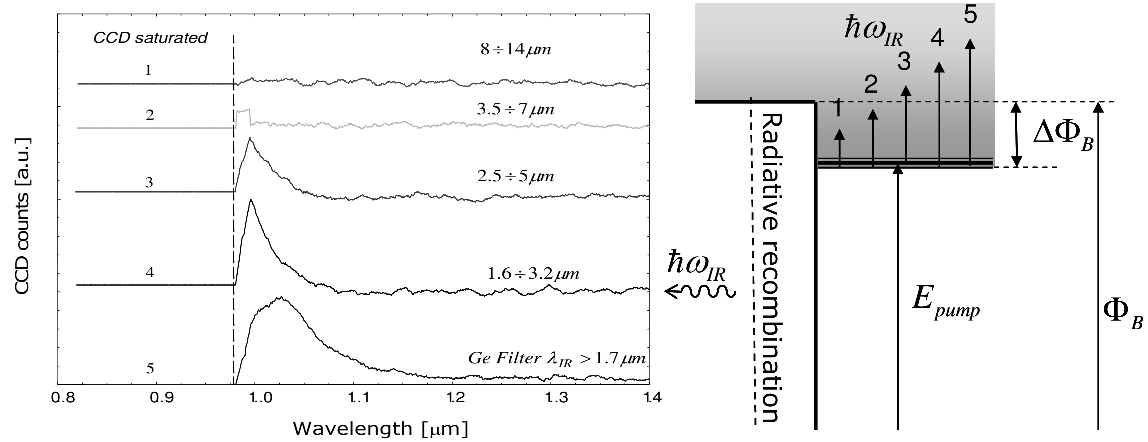

Figure 4: IR-induced visible luminescence, proving conversion and non-equilibrium free carrier distribution. Non-equilibrium carriers, excited by IR photons with energies $\hbar\omega_{IR} \geq \Delta\Phi_B$, are emitted into the matrix material, where they recombine radiatively

3. THE POTENTIAL RAMIFICATIONS OF SIRICA'S INNOVATIVE IR DETECTOR

The manufacturing process for Sirica's detectors is silicon-compatible. Such detectors would not require cooling nor vacuum packaging and would still meet with the most challenging performance specifications, at prices favorable to those of the most advanced thermal detectors, and with substantial additional improvements in size, weight and handling capabilities.

The implementation of Sirica technology would result in a major cost reduction that can drive a great impact on all existing high-end as well as low end IR applications. Costs of cameras/systems designed for night vision applications could be reduced by significantly replacing current IR sensors and cooling systems with Sirica's uncooled IR sensor, *without compromising on performance specs*.

Military markets for very high end applications are willing and capable of paying for the best cooled detectors priced at >>$10K range (system price >>$50K), but the overall number of such systems is greatly limited (100-1000 systems per program). Uncooled microbolometers developed in the last decade opened the markets for mid and low end applications, where detector price is still >>$1K where the camera cost is ~ $3k for commercial automotive, and $6K - $20K for military applications.

Sirica technology with detector priced at $100's (and potentially lower) would enable extremely low cost night vision systems (camera cost <<$500), opening previously unreachable mass market applications such as driver night vision enhancement for the automotive industry, perimeter security (parallel to the $1B market for CCTV) and every soldier applications.

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