Requirements and design considerations of UV and X-ray detectors for astronomical purposes

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ABSTRACT

Since our previous review, new developments have occurred which make it interesting to compare wide bandgap semiconductors with low (sub 0.1 K) temperature detectors. We compare the strengths and weaknesses of each of these devices. We show that there is a need for both types of devices. Furthermore, single or small-array versions of the low temperature devices have been shown to work as single photon-counting devices. This gives the low temperature devices a distinct advantage over wide bandgap detectors. The ability to operate at room temperature and to be able to use standard indium bump bonding techniques to allow for relatively routine fabrication of 500 $\times$ 500 (or larger) pixel formats should, however, provide impetus to further development of wide bandgap semiconductor devices.

Keywords: X rays, ultraviolet, superconducting, wide bandgap semiconductors

1. INTRODUCTION

Over the past 10 years major advances have been made in the development of sub 0.1 K devices as photon detectors. At the same time, materials applications have developed wide bandgap semiconductors that show great promise for use as photon detectors. Up until a few years ago, the wide bandgap devices and CCDs were the focus of most attention for detectors in the approximately 700 nm through the 100 nm wavelength range, and low temperature devices were being developed primarily as X-ray detectors or as weakly interacting particle (WIMP) detectors (cf. ref. 1, also the entire volume A370 of NIM in Phys. Res., 1996). Low temperature devices are now being developed, however, for use all the way down to the approximately 1000 nm wavelength range, and it is therefore appropriate to compare the attributes of these two extremely divergent technologies: wide bandgap semiconductors and low temperature devices.

For the sake of brevity we will not describe many of the details of these devices (see ref. 1, 2, 3, and references therein) nor will we discuss many of the engineering requirements necessary to make these devices work. We focus instead on several main areas of concern for the low temperature devices that make it important to still consider development of wide bandgap semiconductor devices: cooling and the related readout electronics for large (500 $\times$ 500 pixel) arrays;

requirements for filters; and the desirability of making the devices 1 cm or larger in diameter.

We will begin with an overview of why astronomers are interested in such devices and therefore what the drivers are for technological development. We will then proceed with an overview of the low temperature devices versus the wide bandgap devices and discuss where the functionality of these two types of devices overlap, and areas where the devices are likely not to compete. We will then proceed to compare the requirement for a working system with each technology in the area of overlap and conclude by judging that *if* wide bandgap semiconductors can live up to their promise, then we can avoid working at low temperatures for UV solar-blind applications where energy resolution with imaging is not important. If, however, limitations due to sensitivity to the infrared and optical can be suppressed enough to avoid pulse pileup (the coincidence of two or more pulses within a pulse integration time which can then mimic a single higher energy event), low temperature devices could be the wave of the future for space applications in the X-ray through the optical.

2. OVERVIEW OF ASTRONOMICAL INTERESTS

We start from the high energy range and work our way down. In the $\sim 0.25 - 10$ keV energy range, the interest lies in studying point sources as well as diffuse sources of emission. In all cases a non-dispersive energy resolution is most desirable and future missions call for energy resolution as good as 2 eV at 6 keV[4]. Besides energy resolution it is also important to make relatively large (500×500) format devices with ~ 50 micron pixel sizes to provide wide field-of-view coverage for survey work as well as the study of such extended objects as supernova remnants and clusters of galaxies (cf. ref. 5). Ideally, these large format devices would have 2 eV energy resolution as well. Although it is not the main focus of this paper, we point out that CCDs have become the device of choice for current missions (cf. ref. 6) and that there is still a need for devices with 4096×4096 formats that provide CCD-type energy resolution (about 140 eV at 6 keV) run at (or near) room temperature (for ease of use lower cost). A study of the diffuse X-ray background could also benefit from a large ($\gtrsim$1 cm) detector that would not have a pixelated format. To allow for the study time variability (e.g., bursting X-ray sources and pulsars), readout speeds in the 1 Meg Hz range are also desirable. The "ideal" detector would have micro-second readout, 2 eV energy resolution, a $\sim 500 \times 500$ (or larger) format with ~ 50 micron pixels. To obtain all of this power, the X-ray astronomer is willing to use low temperature devices. There is also room, however, for a CCD replacement with a pixelated device with CCD-type energy resolution, but with individual pixel readouts, and if it could run at room temperature, this would further reduce the cost of such a device.

In the UV, non-dispersive energy resolution is desirable but relative $(\Delta E/E)$ values as good as can be obtained in the X rays do not seem possible. Therefore, the UV astronomer has so far concentrated on design attributes such as higher quantum efficiency and solar blindness. Examples of the type of science that would be done in the ultraviolet would be surveys for UV bright objects, and imaging relatively nearby galaxies in the UV to compare with distant galaxy images whose equivalent rest energy we observe is in the UV[7]. Relatively broad-band energy resolution seems possible and it would be interesting to allow for broad-band redshift estimation (cf. ref. 8 and 9) and order separation for grating work as well as solar blindness. Given the current state of UV astronomy, however, a first step of greatly improved quantum efficiency and solar blindness is called for.

In the optical ($\sim$ 350 nm to 700 nm), CCDs have worked very well. The requirement that the ground-based astronomer collect data at an even faster rate calls for broad-band energy resolution with imaging. Again, as with the UV, the applications of broad band energy resolution include redshift determination and order separation in grating work, but as the wide bandgap detectors do not work in this wavelength range, we will not continue to discuss applications in the optical.

3. DETECTOR TECHNOLOGY; A REVIEW OF CONCEPTS

3.1. Overview

As noted above, we will not describe the details of the various technologies here. Simplistically, the basic physics underlying the wide bandgap versus the low temperature devices is quite different. In the low temperature case free charge can be created by the breaking of Cooper pairs. The excitation energy required to create a "free" charge is about 1 meV and this small ratio of energy to free charge means that the device has the potential for extremely good energy resolution (about 1 eV at 6 keV). The wide bandgap devices require a relatively large amount (about 3 eV) to raise an electron to the conduction band. This means that these devices cannot provide the energy resolution of the low temperature devices. And it is not clear that the excitation process in the wide bandgap semiconductor would produce an amount of free charge that would be proportional to the energy of the incident photon. But *if* this were the case, then at X-ray energies (1–10 keV) the energy resolution based on $\sim$ 3 eV per free charge should be comparable to CCDs which produce resolution equivalent to about 3 eV per electron charge (cf. ref. 6). The advantages of the wide bandgap are: it would be possible to operate without an optical filter; it could also be possible to operate at room temperature (noise reduction in the readout electronics might still require some cooling); it should be possible to make a radiation hard device; and, it should be possible to fabricate a pixelated device with a parallel readout (individual pixel readout versus serial readout for the CCD).

3.2. Low temperature devices

The bolometer-type (micro-calorimeter) devices have been developed to the point where they have been used effectively to produce the best energy resolution of any non-dispersive X-ray detection system (cf. ref. 3). The best energy resolution achieved is about 7 eV at 6 keV. In contrast, the superconducting tunnel junction (STJ or SIS = superconductor insulator superconductor) detectors have never achieved their promise of comparable or better energy resolution as their best is about 30 eV at 6 keV in the X-ray regime. A low baseline noise allows these STJs and transition edge sensors (TESes; a modern form of micro-calorimeter, see ref. 2 and 3, and references therein) to be used as photon detectors all the way down to the near infrared. The ESTEC group[8] has been working on SIS detectors and has made such good progress that they suggest flying such a device as an advanced camera for the Hubble Space Telescope 2002 upgrade mission[8]. The TESes may evolve to the detector of the future. The difficulty for providing energy resolution in a pixelated format is that TESes work on the principle of operating on the edge of the transition between being superconducting and normalconducting and this places requirements (whether these are too severe or not is yet to be determined) on maintaining temperature control and material quality uniformity (material impurities lead to variations in their critical temperature) throughout the array. For 100 kHz or faster readouts, the SIS detectors traditionally were favored over the micro-calorimeters, but since TESes are, in fact, micro-calorimeters, then micro-calorimeters too can achieve, in theory, counting rates in the 100 kHz range (cf. ref. 3). The energy resolution of these low temperature devices in the UV and optical is about 20% of the energy, and such systems obviate the need for filters and therefore may have applications for ground-based astronomy as well as X-ray and UV astronomy[8]. With the potential for energy resolution these low temperature devices can, in principle, be used as solar-blind detectors. This brings STJs (and TESes) in direct competition with wide bandgap semiconductors that have been proposed as UV solar-blind detectors. We will see how these devices compare, below, but first we provide a short review on the wide bandgap devices.

3.3. Wide bandgap materials

Previously, we (ref. 7; see also ref. 10 and 11) have proposed wide bandgap GaN (gap about 3.4 eV) or AlGaN (gap about 6.2 eV) semiconductors as the material of choice for future astronomical detectors. In principle, devices made with these materials (or diamond) would have 80–90% quantum efficiency above the bandgap and negligible efficiency below. Photo-conductors and Schottky barrier devices have been produced and tested (cf. ref. 10 and 12) but the devices have only been tested with relatively intense laser beams, and the more desirable pin-diode configuration which could then be fabricated into a CCD-type pixelated device[7] has never been built. Besides a solar-blind detector for UV astronomy (or practical/industrial applications such as flame detection), these materials could also, in principle, be fabricated into devices that could supplant photon-tubes for UV detection, and, as noted above, they also have the potential to supplant CCDs as X-ray detectors.

4. ENGINEERING REQUIREMENTS

4.1. Low temperature devices

We now discuss just some of the hurdles that must be overcome in using the low temperature devices. We will only mention general effects caused by the physics of how these devices operate. We will ignore such details as etching, wire bonding, material purity, etc., which can be difficult but can, in principle, be accomplished.

First and foremost, the low excitation energies that produce the free charge require that these devices operate at sub 100 mK temperatures. If a 500×500 pixel array (or larger, i.e., second-generation sized CCD-type formats) is to be built, then the design that is called for is either pulling 2.5×10^4 wires out to higher operating temperatures and using JFETs, or using on-chip electronics. In the latter case, the on-chip electronics must not consume so much power as to overwhelm the dewar/refrigerator system which must maintain the detector chip at 100 mK or lower. The technology for large formats has not yet been developed, but there is certainly interest in such a device and some possible options have been discussed[5,13]. An alternative is to be able to use crystal absorbers and greatly reduce the number of detectors needed (cf. ref. 14), but such systems are far from mature.

Another implication of the low temperature device meV "bandgap," is that these devices must use a blocking filter to stop the long wavelength radiation from swamping the detector signal. Yet, at the same time, this filter must be able to pass the desired signal that the detector is designed for. For near UV (350 nm) ground-based work, the combination of the emissivity of the earth's atmosphere and the telescope itself will require a filter that is approximately 10^6 effective at stopping about 20 micron radiation and yet nearly 100% transparent to 500 nm radiation. Moving into space would avoid the atmospheric background. This, combined with a mirror cooled to about 30 K, could alleviate much of the IR background.

At X-ray wavelengths, the difficulty for the SIS detectors is that they are too thin to fully absorb 1 to 10 keV X rays. Also, in the optical, they have the problem that superconductors are metals which means, perforce, that they are "shiny," i.e., they are very reflective to visible wavelengths. The reflectivity at optical wavelengths, however, may actually help make the low temperature detectors more solar blind.

The requirement for a solar-blind UV detector for astronomy is that it have an effective quantum efficiency of 10^{-8} below the detector cut-off. This is because many astronomical sources are 10^8 times brighter in the optical than in the UV (cf. ref. 7). Thus, for the low temperature detector to work in space with a cooled mirror and no filter, it requires that there be no pulse pileup from the observed sources, which means that the sources must be faint enough that fewer than about 2 optical photons are received within an integration time of about 10 microseconds, and this means that the typical UV counting rate will be about 10^{-8} per 10 microseconds or 10^{-3} counts per second. This constraint demonstrates the limitation of low temperature photon counters as UV solar-blind detectors.

In summary, the difficulty in manufacturing these devices aside, the engineering requirements of low (sub 0.1 K) temperature devices are: (1) maintaining the low temperature, especially if large format arrays with on-chip electronics are required; (2) devising a readout scheme for large formats; (3) infrared filters for optical/UV use; (4) thick enough devices for X-ray absorption; and (5) making detectors that have dimensions of 1 cm or larger.

4.2. Wide bandgap devices

First and foremost, the materials need to be made in quantity with the requisite quality. Photo-conductors would be relatively straightforward to fabricate as they only require n-type material (the easiest to make). However, for low light level or single photon counting, the weak signal in the photo-conductor might not be sufficient to allow these photo-conductors to be used in such a mode. Fabrication of a pin-diode array and indium bump bonding for readouts is the design of choice, but this then requires the ability to fabricate high quality i- and p-type materials as well, which is even more difficult. Non-pixelated devices might be able to compete with currently available optical pin diodes, but again the weak signal might prohibit the use of photo-conductor systems. As the saturation velocity in these materials is only slightly larger than that in Si (cf. ref. 11), wide bandgap devices should be able to operate at sub 10 nano-second speeds.

Pin diodes fabricated from wide bandgap materials would be an improvement in efficiency compared to the photo-tubes in the 350 nm range, and they would function better in the nano-second range than photo-tubes. Whether these devices can be made thick enough (about 0.5 mm or thicker) to be effective X-ray detectors, and whether or not they would provide adequate energy resolution remains to be seen. If they can, then potentially they can compete with CCDs in that the theoretical energy resolution should be comparable. So far, the limitation of the wide bandgap devices seems to be primarily in the manufacturing end. The one exception is the inability to provide energy resolution comparable to the low temperature devices, as the bandgap strictly limits the initial number of free charge carriers. To summarize this section: the wide bandgap materials have the inherent physical attributes that are likely to provide the best UV solar-blind detectors where solar blindness and pixelation, rather than energy resolution, are important. It is also intriguing to explore possibilities of using the wide bandgap materials as X-ray detectors and as improved near-UV pin diodes or photo-conductors with sizes of 1 cm or larger.

5. CONCLUSION AND SUMMARY

In summary, the one real physical limitation of the wide bandgap devices compared to the low temperature devices, is that the energy resolution of the wide bandgap devices will never be as good as the low temperature devices. The major pluses for the wide bandgap devices are that they work at room temperature rather than at sub 0.1 K, and that they are truly solar blind which allows them to observe much brighter objects without filters. Conversely, energy resolution is a desirable feature to have in an imaging device, and the low temperature devices offer the best hope in this area. If moderate energy resolution and 1 cm-sized detectors are necessary, then wide bandgap semiconductors may be useful. It remains to be seen if there are enough economic drivers or scientific drivers from industry, or the government, to supply the funding necessary to bring wide bandgap detectors to the market.

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