HgCdTe Arrays for the Far-Infrared

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INTRODUCTION

The development of focal plane arrays (FPAs) has dramatically increased the sensitivity and efficiency of large optical and infrared telescopes. For the 1-2.5 mm band, the 1Kx1K HgCdTe "Hawaii" chip is the largest operational array in astronomy. Similar arrays of 2Kx2K are now in development, with the goal of assembling an 8Kx8K mosaic array for the Next Generation Space Telescope (NGST) project (Hall 1998). The spectral versatility of the HgCdTe alloy is well recognized for wavelengths as long as the Long Wavelength Infrared (LWIR) band from 8-20 mm. What is not so recognized, however, is that theoretically there is no long wavelength limit for appropriately composed HgCdTe. Only one serious effort appears to have been made to apply this material at far-infrared (FIR) wavelengths between 20-150 mm. Spears (1988) successfully demonstrated a photoconductive response from HgCdTe at 120 mm, but this pioneering effort was never followed up, in part because of the difficulty of controlling the HgCdTe alloy composition in bulk crystals. With the advent of precise molecular-beam-epitaxy (MBE) of HgCdTe in the early 1990s, it is now appropriate to reconsider this semiconductor for detector applications well longward of the 20 mm LWIR band cut-off. We wish to develop large FPAs for photometric imaging at high spatial resolution. The astrophysical subjects are molecular cloud complexes with temperatures of 30-100 K, and corresponding peak emission wavelengths between 50 and 150 mm. Because the Earth's lower atmosphere absorbs strongly at these wavelengths, the observations must necessarily be done from airborne, balloon-borne, or space-borne platforms.

Existing Technology

For LWIR applications between 8-20 mm, 256x256 arrays of As:Si Impurity-Blocked–Conduction (IBC) detectors are the state-of-the-art. The long wavelength cut-off can be extended to 37 mm with Sb:Si IBC arrays, but dark currents are not as good. Some development for SIRTF has been done on Ga:Ge IBC detectors that work from 80-180 mm, but multiplexed arrays have not been fabricated (Watson *et al.* 1993). The largest FIR array is the 32x32 element Ga:Ge hybrid array that has been built for the l=70 mm channel of the MIPS instrument on SIRTF. It consists of 8 bars of 4x32 elements arranged in a stacked format. For imaging at 160 mm, MIPS will stack 4 2x5 detector modules to make a 2x20 stressed-Ga:Ge assembly. Of course none of these Ga:Ge detectors are planar film devices; they are fabricated from bulk materials. To prevent excessive dark current, doping levels are kept low. As a consequence, the absorption strength is low (1 cm^{-1}), and path lengths must be at least 2 mm (with total internal reflections) to get good quantum efficiency. Although these extrinsic photoconductive detectors have excellent sensitivities, their bulk nature severely restricts the practical size of an array.

New Technology

What is needed for FIR wavelengths is an intrinsic rather than extrinsic detector material. Fortunately, alloys and superlattices made from HgTe and CdTe can be fabricated with bandgaps engineered between -0.26 eV and 1.60 eV (corresponding to DC to 100 THz response). The absorption coefficient of intrinsic HgCdTe is about 100 cm^{-1} in the l=50-150 mm range, and so devices as thin as 5-10 mm can provide good quantum efficiency. There appears to be no fundamental reason why FIR FPAs could not eventually be fabricated as large as 1Kx1K pixels, similar to the current optical/near-IR standard.

The development history for HgCdTe at FIR wavelengths is brief, but promising. In 1988 Spears selected $Hg_{1-x}Cd_xTe$ wafers with x=0.168 from a bulk ingot grown with an alloy composition gradient. Photoconductors fabricated from this material with resonant back reflectors, when measured at T=9 K, had quantum efficiencies (QE) of 7% at **l**=70 **m**m and 4% at **l**=118 **m**m. The extrapolated quantum efficiency was 55% at **l**=58 **m**m and 12% at **l**=105 **m**m (resonant peaks). The long wavelength response was compromised by band filling effects produced by residual n-type impurities. This problem can be alleviated by going to low-doped p-type material.

Bandgap Engineering

No simple (single or binary) semiconductor material has a direct bandgap with the requisite 10 meV energy needed for a photoconductive response in the 50-150 mm wavelength range. Fortunately, a solution exists with ternary compounds, and two approaches are available. The first is the well-known alloy process in which the bandgap is tailored by varying the mole fraction x of CdTe in an $Hg_{1-x}Cd_xTe$ alloy. The second is a superlattice structure, in which the bandgap is determined by the thickness and number of alternating HgTe and CdTe (or HgCdTe) layers in a composite semiconductor.

$Hg_{1-x}Cd_xTe$ Alloys

At 77 K, the band gap of the semimetal HgTe is –0.26 eV, and that of the semiconductor CdTe is 1.6 eV. These materials can be combined with various fractional compositions x to tune the bandgap E_g(eV) of the $Hg_{1-x}Cd_xTe$ alloy according to the formula (Hansen and Schmit 1983):

$$E_g = -0.302 + 1.93x + 5.35\times10^{-4}T(1-2x) - 0.810x^2 + 0.832x^3.$$

Figure 1 shows the cut-off wavelength, defined as l$_{co}$(mm)=1.24/E_g(eV), as a function of fractional composition x at various temperatures. For the approximate 0.01 eV band gap needed for **l**=100 **m**m response, x would be close to 0.17. As the band gap approaches zero, small fractional changes in x lead to large fractional changes in the gap energy, and generally we need to control x to within 0.2% to have a 10% uncertainty in peak response. It should be apparent that compositional inhomogeneities in this case lead to variations in the gap throughout the material resulting in non-uniformity in the response of array detectors. Nevertheless, adequate control can be achieved with MBE techniques. For example, de Lyon *et al*. (1998) used MBE to fabricate a 64x64 element HgCdTe array on a 61 **m**m pitch. The array was designed for the 4 **m**m band, for which x=0.351. The uniformity of the detector cut-off wavelengths indicated that the variation in x over the array was no larger than ¶x = ± 0.0006. If we take the same absolute x-uniformity for a composition with mean x = 0.171, then the variation in cut-off wavelength for a **l**=100 **m**m array (worst case example) is no larger than 5%. We could tolerate variations 3 times as large for our applications.

The array elements will be reverse-biased photodiodes. To form the diodes, the alloy is doped with n- and p-type regions. For the long wavelength (small bandgap) devices of interest here, control of doping and defects is more challenging than at shorter wavelengths because tunneling currents are more of a problem. The superlattice approach described below should be superior to alloy fabrication for minimizing these unwanted currents.

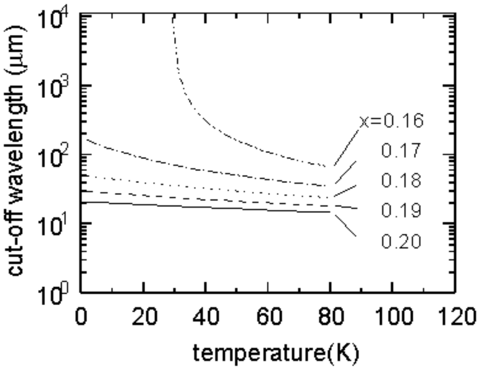

Fig.1

Superlattices

In a superlattice (SL) device, the bandgap is controlled by adjusting the thickness of alternating material layers with very precise molecular-beam-epitaxy (MBE) techniques. Superlattices have a number of advantages over simple alloy semiconductors:

> (1) the band gap of the SL is much easier to control than that of the alloy because it is the layer thickness rather than the mole fraction of the deposition material that must be controlled precisely;
> (2) since growth-direction effective masses of electrons and holes in SL are decoupled from the band gap, FIR detectors with larger effective masses should display order(s) of magnitude reductions in the tunneling current. If tunneling currents can be reduced as predicted with the SL structure, then photodiode (PD) devices may become practical out to 100 mm and perhaps 150 mm wavelength;
> (3) carrier degeneracy (bandfilling) effects near the long wavelength band edge are less significant; and
> (4) the SL structure can suppress Auger recombination at long wavelengths by intentionally inducing strain.

HgTe-CdTe superlattices (SLs) were first proposed by Schulman and McGill (1979) as promising new infrared devices. Although MBE deposition of telluride compounds has been available since the mid-1980s, no work with ultra-small gap energies has been attempted. For low band gap device fabrication (E_g=0.01 eV), we believe the superlattice approach will produce detectors with superior performance and ease of fabrication compared to alloy devices. The Microphysics Lab at UIC earlier studied quite a few aspects of the II-VI SLs (Mahavadi *et al.* 1990; Sporken *et al.* 1989; Wang *et al.* 1996). Potential problems such as the fragility of HgTe layers and possible diffusion of Hg into adjacent CdTe or HgCdTe layers have been solved with advances in process techniques. For example, transmission electron microscopy (TEM) studies of vertical cross-sections of HgTe/HgCdTe superlattices show no evidence for Hg interdiffusion for low substrate temperatures (T<170 ^{o}C) (Leopold *et al.* 1988; Lansari *et al.* 1989).

Goals

We intend to fabricate both alloy and superlattice photodiode detectors. The first detectors will have cut-off wavelengths in the 50-60 **m**m band, and have direct contacts for DC and FIR parameter evaluation. Successful results will lead to fabrication of a 32x32 element photodiode array with 80 **m**m pixels that will be bump bonded to a CMOS multiplexer. FIR radiation can be coupled into these small pixels via a Si immersion lens, which magnifies the pixel size by a factor of 3.4. Next we will fabricate a 32x32-element array optimized for the 100 **m**m band. Success with small arrays will lead to a 128x128 or larger design. The UIC Microphysics Lab is currently funded by the Army Research Lab to develop 256x256 hybrid arrays (bump bonded to multiplexer) for LWIR applications and supported by the US C&C Night Vision Lab to develop monolithic 128x128 element arrays also for the LWIR.

One final point is that should good photodiode (PD) pixels be difficult or impossible to fabricate at the longest wavelengths of interest (perhaps because of excessive tunneling currents in the lowest bandgap materials), we have a fallback position of using photoconductive (PC) detectors. Peak electric fields in PC devices are a factor of 10 less than those in reverse-biased PDs. However, PCs have lower impedances and are current biased, which increases the power dissipation of an array. Given that only a certain thermal load can be tolerated, it seems clear that PC detectors will be limited to relatively small FPAs, perhaps no larger than 32x32 elements. Individual (unmultiplexed) readouts such as the Hughes CRC-696 used on MIPS/SIRTF will be needed. Whether the dark current of a HgCdTe PC can be low enough to work with this particular readout chip remains to be seen. Nevertheless, even a small array would be of significant benefit to astronomy in the 100-150 mm wavelength region where the only available photoconductors are stressed-Ge devices. We believe that PC HgTe/HgCdTe with the SL structure could make stressed Ga:Ge obsolete. Although the SL effort might be described as *high risk*, it offers a commensurate *high payoff*.

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