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Compact-Fire Infrared Radiance Spectral Tracker (c-FIRST)

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ABSTRACT

Remote sensing of wildland fires is required for many cross-disciplinary science investigations including wildland fire impacts on ecology. For decades this research has been hindered by insufficient spatial resolution and detector saturation at short and mid-infrared wavelengths where the spectral radiance from high temperature (>800 K) surfaces is most significant. To address this, we're developing a compact high dynamic range (HDR) multispectral imager. The Compact Fire Infrared Radiance Spectral Tracker (c-FIRST), which leverages digital focal plane array (DFPA). The DFPA is hybridized from a state-of-the-art high operating temperature barrier infrared detector (HOT-BIRD) and a digital readout integrated circuit (D-ROIC), which features an in-pixel digital counter to prevent current saturation, and thereby provides dynamic range (>100 dB). The DFPA will thus enable unsaturated, high-resolution imaging and quantitative retrievals of targets with a large variation in temperatures, ranging from 300 K to >1600 K (flaming fires). With the resolution to resolve 50 m-scale thermal features on the Earth's surface from a nominal orbital altitude of 500 km, the full temperature and area of wildland fires and the cool background are captured in a single observation, increasing science content per returned byte. The use of a non-saturating FPA is novel, overcomes previous problems where high radiance values saturate FPA pixels (which diminishes the science content), and demonstrates a breakthrough capability in remote sensing. Thus, c-FIRST is suitable for quantifying emissions from wildland fires, which is critical for establishing their impact on ecosystems at global scales. The FPA for the c-FIRST was fabricated using InAs/InAsSb HOT-BIRD epitaxial material into 20μm pixel pitch, 1280x480 format detector arrays and hybridized to analog DROIC. The 50% cutoff of the DFPA is at λ~4.5um and the measured external QE~50% across the full QE spectrum at 140K operating temperature. We fix the integration time at 6 ms in order to obtain good sensitivity in the MWIR bands when observing normal 300K background scene at 150 Hz frame rate. For a standard analog ROIC, the detector pixels are easily saturated at target temperatures ~700 K. With the D-ROIC operating in the 16-bit mode, we can increase the saturation temperatures significantly to ~1100 K. With the D-ROIC operating in the ultra-HDR 32-bit mode (28 trillion e- well depth), the detectors do not come near to saturation even for 1600 K targets. A critical metric for remote sensing of fires is the minimum detectable target size. The c-FIRST would provide an order of magnitude improvement in the minimum size of a detectable fire, primarily due to the spatial resolution of the non-saturating detector than the current servicing instruments such as Advance Baseline Imager on GOES, etc. with reduced power, size, and weight. c-FIRST airborne flights for instrument test and validation scheduled for 2024 fire season. We're expecting c-FIRST space validation based on a space technology validation opportunity in 2026 or later.

INTRODUCTION

Remote sensing and characterization of high temperature targets on the Earth's surface is required for many cross-disciplinary science investigations and applications including wildland fire and volcano impacts on ecology, the carbon cycle, and atmospheric composition. For decades this research has been hindered by insufficient spatial resolution and/or detector saturation of satellite sensors operating at short and mid-infrared wavelengths (1-5 µm) where the spectral radiance from high temperature (>800 K) surfaces is most significant.

To address this critical need, the NASA Jet Propulsion Laboratory is developing a compact modular high dynamic range (HDR) multispectral imager concept, with the flexibility to operate in the short, mid- or long-wavelength infrared spectral bands. The goal of this NASA Instrument Incubator Program (IIP)-21 funded project is to demonstrate this novel technology through the maturation of a mid-wavelength infrared (MWIR) imager, the Compact Fire Infrared Radiance Spectral Tracker (c-FIRST), which leverages digital focal plane array (DFPA) development from the Advanced Component Technology (ACT) Program. The DFPA is hybridized from a state-of-the-art high operating temperature barrier infrared detector (HOT-BIRD) and a digital readout integrated circuit (D-ROIC), which features an in-pixel digital counter to prevent current saturation, and thereby provides very high dynamic range (>100 dB). The DFPA will thus enable unsaturated, high-resolution imaging and quantitative retrievals of targets with a large variation in temperatures, ranging from 300 K (background) to >1600 K (hot flaming fires as shown in Figures 1 and 2). With the resolution to resolve 50 m-scale thermal features on the Earth's surface from a nominal orbital altitude of 500 km, the full temperature and area distribution of fires and active volcanic eruptions and the cool background are captured in a single observation, increasing science content per returned byte.

Figure 1: This figure shows a flaming wildland fire as seen from a visible camera. Image is unsaturated.

The use of a non-saturating detector is novel, overcomes previous problems where high radiance values saturate detectors (which diminishes the science content and usefulness of the data), and demonstrates a breakthrough capability in remote sensing – one with broad applicability in both terrestrial and planetary settings. By incorporating this technology, c-FIRST is suitable for quantifying emissions from fires and volcanic eruptions of different temperatures and intensities, which is critical for establishing their impact on ecosystems, carbon fluxes, and air-quality at local scales and climate at global scales.

Figure 2. This image shows a wildland fire as seen from a standard 1-5.5 micron mid-wavelength infrared (MWIR) camera. Most of the pixels which detect the flaming fire are saturated due to the overwhelming MWIR signal from the fire. The over whelming signal quickly saturates the well depth of the read out integrated circuit of the focal plane array.

The MWIR BIRD structure would have two n-type region (n) separated by a larger bandgap, undoped barrier layer (B), where the n-B heterojunctions have a larger conduction band offsets and zero valence band offsets. [1-2] Such a barrier would block majority carrier electrons, but pass photogenerated holes. The nBn infrared detector is designed to reduce dark current (noise) without impeding photocurrent (signal). Central to the nBn operation is the strong suppression of generation-recombination (G-R) dark current due to Shockley-Read-Hall (SRH) processes. The nBn infrared detector is designed to reducing dark current (noise) without impeding photocurrent (signal).

BARRIER INFRARED DETECTORS

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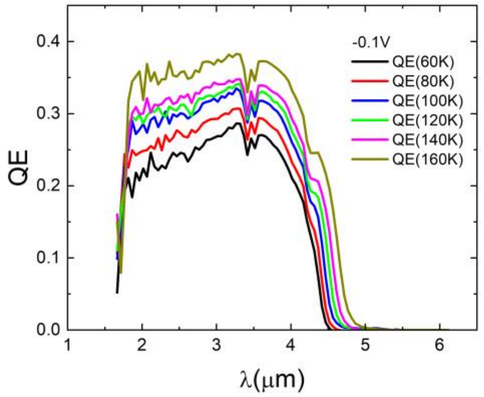

Figure 3. Backside illuminated spectral quantum efficiency (QE) for an MWIR detector measured at temperatures ranging from 60K to 160K.

Another important aspect of nBn and related structures is their effectiveness in reducing surface leakage current. The top surface of the active narrow gap absorber in the nBn detector is covered by the wide band gap barrier layer, and therefore does not need additional passivation to suppress surface leakage [1]. In a focal plane array (FPA) configuration, the array of top contacts could be defined by etching through the top contact layer but not the barrier layer [1]. In this configuration, the narrow gap absorber is not exposed, and therefore does not contribute to surface leakage. Finally, even in a deep-etched mesa configuration, where the side walls of the narrow gap absorber are fully exposed, the barrier can still block electron surface leakage effectively [1-2]. An important aspect of the nBn detector (and unipolar barrier detector architecture in general) is the ability to block majority carriers without impeding the flow of minority carriers.

The InAs/InAsSb (Gallium-free) T2SLS has emerged as an alternative adjustable bandgap, broad-band III-V IR detector material to the more established InAs/GaSb type-II superlattice (T2SL). Recently, there has been growing interest in this material as an infrared detector absorber due to longer MWIR and LWIR minority carrier lifetimes in InAs/InAsSb strained-layer superlattice (SLS) than in InAs/GaSb superlattice (SL) and demonstrated an InAs/InAsSb SLS LWIR photodetector based on the nBn device design [2]. The T2SLS material can be grown on InAs or GaSb substrates, GaSb is available in 2”, 3”, 4” and 6” diameters formats.

MWIR FOCAL PLANE ARRAY FOR C-FIRST

An InAs/InAsSb SLS nBn structure was grown on a 4-inch diameter low Te-doped GaSb (100) substrate in a Veeco Applied-Epi Gen III molecular beam epitaxy (MBE) chamber equipped with valved cracking sources for the group V Sb2 and As2 fluxes. The nBn architecture is used for G-R and surface-leakage dark current suppression. Square mesa photodiodes of area 250μm x 250μm were fabricated along with detector arrays for responsivity and dark current measurements. The devices were not passivated nor treated with anti-reflection coating. Figure 3 shows the spectral quantum efficiency (QE) derived from back-side illuminated (through the GaSb substrate) spectral responsivity measured at temperatures ranging from 40K to 80K; the QE has not been corrected for substrate reflection or transmission. Accordingly, the spectral QE for 60K and 160K was taken at -100mV. The cutoff, taken at the wavelength at which the QE is 50% of that at λ~4.5μm.

The FPA for the c-FIRST engineering model (EM) was fabricated using those MBE grown epi-material into 12μm pixel pitch, 1280x1024 format arrays and hybridized to the FLIR-1308 analog readout integrated circuit (ROIC). The purpose of this analog FPA is to test the optical and thermal properties of the c-FIRST instrument.

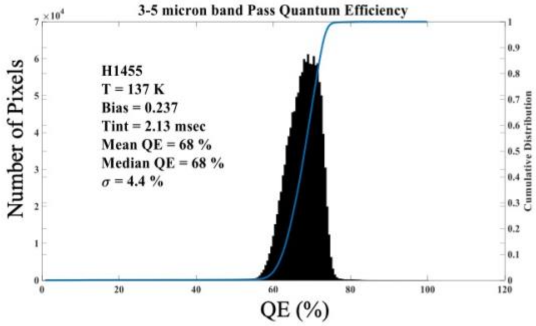

Figure 4. 3-5μm broad-bandpass filter QE of the c-FIRST BIRD focal plane array (FPA) at 137K.

Figure 4 shows the 3-5 μm broadband QE of the c-FIRST EM FPA. The noise equivalent temperature difference (NEΔT) provides the thermal sensitivity of an infrared imaging system and it is a very useful diagnostic tool to evaluate the full operational performance available. It is defined as the minimum temperature difference required at the target to produce unity signal-to-noise-ratio. Sequence of consecutive frames is collected for equivalent noise determination as well as other optical properties of FPA. The photo response matrices of FPA is derived at the low and high blackbody temperatures (i.e., 295 K and 305 K), and temporal noise matrix of FPA is estimated at the mid-point temperature by taking 64 frames of data. The temporal NEΔT of pixels are numerically evaluated from the relations, $NE\Delta T = \sigma_{Temporal}\Delta T/[Mean(T_H) - Mean(T_L)]$. The mean signal $Mean(T_L)$ and $Mean(T_H)$ are evaluated at blackbody temperatures of $T_L = 295$ K and $T_H = 305$ K. The temporal noise is measured at 300K using 64 frames, and ΔT ~10 K.

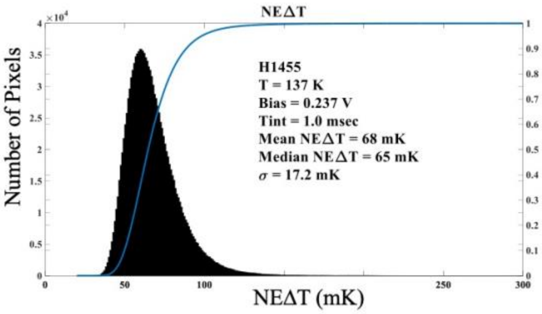

Figure 5. Noise equivalent temperature difference (NEΔT) of the c-FIRST EM FPA at 137K.

The experimentally measured NEΔT histograms distributions of 1280x1024 pixels MWIR c-FIRST EM FPA at 137K operating temperature with blackbody temperature of 300 K and f/4 cold stop is shown in the Figure 5.

DIGITAL READ OUT INTEGRATED CIRCUIT

Infrared FPAs generally use non-silicon detector arrays to convert the infrared signal into an electrical signal. These detector arrays are hybridized via indium bump bonding process to a ROIC. Conventional ROICs are based on analog electronic circuits. The modern ROICs are D-ROICs. Conventional analog ROICs store charges at individual ROIC pixels and route them out via output taps to off-chip analog-to-digital converters (ADCs) or route them to on-chip column parallel ADCs. This method requires a very large ROIC in-pixel well depth to achieve high signal-to-noise-ratio (SNR). In D-ROICs the charges get digitized at ROIC individual pixel level with a counter by incrementing each time a small charge bucket gets filled. Ideally, this could provide a very high effective well depth for D-ROIC pixels compared to conventional analog ROIC pixels. Total well depth of D-ROIC pixel is given by the size of the charge bucket times the number of counts of the in-pixel counter [3].

DFPA is crucial for enabling new fire/volcano science. Figure 6 shows the calculated number of electrons collected by a 20-µm×20-µm detector pixel for several SWIR and MWIR bands of interest as functions of target black-body temperature (no reflected sunlight contributions). For the calculation we fix the integration time at 6 ms in order to obtain good sensitivity in the MWIR bands when observing normal 300K background scene at 150 Hz frame rate. For a standard analogue ROIC (~10 Me- well depth), the detector pixels are easily saturated at target temperatures of ~400 K and ~700 K, respectively for the MWIR and SWIR bands. With the proposed D-ROIC operating in the 16-bit mode (426 Me- well depth), we can increase the saturation temperatures significantly to ~700 K and ~1100 K. With the D-ROIC operating in the ultra-high dynamic range 32-bit mode (28 trillion e- well depth), the detectors do not come near to saturation even for 1600 K targets.

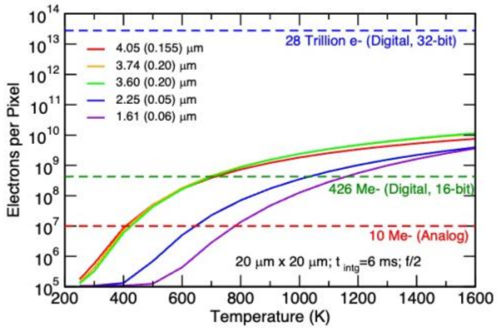

Figure 6. Number of electrons collected per detector pixel as a function of target black-body temperature for different spectral bands; the center wavelength & band width are indicated in the legend; dashed lines indicate ROIC well depth.

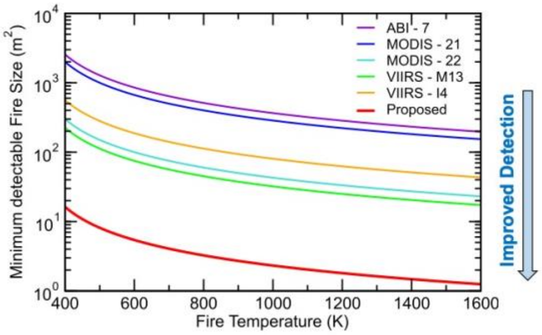

Figure 7. Minimum detectable fire size as function of fire temperature for existing and the proposed C-FIRST instruments.

A critical metric for remote sensing of hot targets is the minimum detectable target size. This is a function of the sensor resolution, the temperatures of the target and background, and the detector sensitivity characterized by the NEΔT. Figure 7 shows these characteristics for the ABI instrument [4] on GOES, the MODIS instruments on Terra and Aqua, the VIIRS instruments [5] on S-NPP and NOAA-20, and the proposed c-FIRST instrument for comparison. Figure 7 shows the minimum detectable size for fires throughout the temperature range expected for landscape fires (380 K for smoldering fires, to 1610

K for extremely hot flaming fires) for an assumed background temperature of 300 K. Note the log scale on the y-axis. The c-FIRST instrument would provide an order of magnitude improvement in the minimum size of a detectable fire, primarily due to the spatial resolution of the non-saturating detector. However, this figure also shows that, even with a worse-case assumed NEΔT, fires on the order of a few square meters can still be detected. Importantly, this means that significant cooling is not required for the focal plane, reducing the power, size, and weight requirements of the c-FIRST package.

Figure 8. C-FIRST optical chamber (with all optical components) during vacuum test.

C-FIRST INSTRUMENT

We just completed the preliminary integration of the c-FIRST optics chamber and the optical components. In addition, we are in the process of applying the anti-reflection coating for the EM FPA and completing the filters for the integrated dewar cooler assembly (IDCA). IDCA for the c-FIRST EM will be completed in the first quarter of the 2024. The full c-FIRST instrument integration will be completed at the end on second quarter of 2024 in preparation for the airborne test during the 2024 fire season (August – September) in western United States. Figure 8 shows the optical chamber during the vacuum test.

SUMMARY

Field testing of c-FIRST EM will involve comparison against known standard materials from the ASTER spectral library and flight testing will involve a short airborne campaign (total flight time 12 hours). Flights will be coordinated with ground crews and simultaneous atmospheric measurements. The instrument will be calibrated both pre and post flight in the laboratory and validated in airborne flight. During validation flights, higher altitude flights (> 3000 m) over fire opportunities will be useful in determining the full dynamic range of the instrument. Aircraft integration costs will be minimized by using the same mounting platform as other JPL developed instruments. In parallel we are developing a 32-bit capable 1280x480 pixel DFPA and it is scheduled to integrate with the same cryocooler in the first quarter of 2025. This DFPA based IDCA is scheduled to integrate with the c-FIRST optics chamber in 2025 4th quarter (i.e., after validating the optics, thermal, and mechanical properties of the c-FIRST EM based on this analog FPA). We're expecting c-FIRST space validation based on a space technology validation opportunity in 2027 or later.

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