

Advanced Sensors for Multi-Color Infrared Imaging Bolometers

C. S. Yung,^{1, a)} G. A. Wurden²

¹National Institute of Standards and Technology, Boulder, CO, 80305, USA

²Los Alamos Plasma Technologies LLC, White Rock, NM 87547, USA

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A new form of infrared (IR) imaging bolometer (IRIB) suitable for radiometric imaging of high temperature plasmas is presented offering several key advantages: instantaneous power read-out via an IR camera (within thermal timescale constraints), increased robustness and uniformity as compared to a traditional imaging foil, ease of calibration, and pixelated imaging. These advantages are accomplished with the use of silicon microfabrication techniques and vertically aligned carbon nanotubes (VACNTs). An additional feature of this approach is the ability to make a multi-color pixel array, which we call the RGB imaging bolometer sensor. By customizing a pattern of individual neighboring pixels with different radiation absorption characteristics, imaging bolometers for multiple energy bands are possible. Since the thin film architecture for each pixel determines its respective photon stopping power, individual pixels can be designed to absorb varying levels of photon energy depending upon the presence of an optical absorber and a thin film stack of varying thickness and atomic number (Z). As a result, we can image three (or more) different energy bands of plasma radiation, simultaneously, with hundreds, if not thousands of lines of sight.

I. INTRODUCTION

A. Background

Segmented infrared (IR) bolometers (SIBs), first conceived in 1996¹, have used the concept of clamping a thin metal foil between two copper plates with drilled holes, to define an array of thermally independent infrared video bolometer (IRVB) pixels.²⁻⁴ The proposed advantage is that the sensor array would no longer require mathematical post-processing to determine temporal heat diffusion across the foil because each pixel would be thermally isolated from its neighbor. The copper plates would act as an isothermal boundary condition to each pixel, and thus each pixel's temperature rise would determine the local irradiance. Recently, multilayer coatings (metal and carbon) on a thick IR transparent sapphire substrate were suggested to be more robust, not need frame by frame mathematical unfolding⁵⁻⁶, easier to fabricate, and more uniform for large sensors.⁷ Despite the lateral or in-plane thermal isolation of this detector, sensitivity was limited by strong thermal coupling to the underlying substrate, even with a rough black carbon coating in between. To this day, unsegmented metal foils remain the "standard" IRVB regardless of the advantage of having a segmented or pixelated metal foil..

This paper describes three new advances to the segmented or pixelated imaging bolometer concept. First, the use of silicon microfabrication techniques developed previously at NIST for radiometers⁸, to create fully monolithic pixelated imaging bolometers. Microfabrication techniques minimize many of the problems associated with

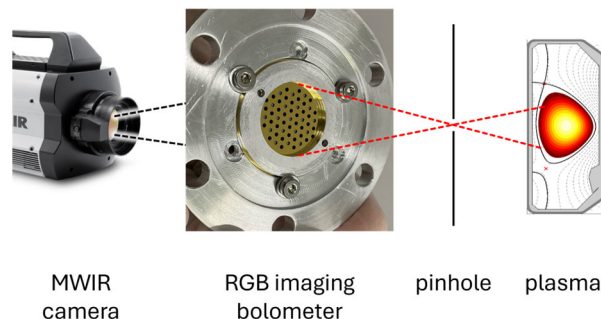


FIG. 1. Schematic of the RGB imaging bolometer for pinhole imaging of a fusion plasma.

metal foil quality/uniformity and effective thermal sinking of the pixels. Vacuum deposited metal now replaces traditional metal foils, resulting in a defect-free, uniformly thick layer that is in intimate thermal contact with a silicon nitride layer grown on silicon. Pixels are then created by etching holes in a silicon wafer thereby creating a metal film/silicon nitride membrane. Second, the use of vertically aligned carbon nanotubes (VACNTs) as an ultra-black⁹ and high emissivity coating¹⁰⁻¹¹ on the front and back sides for high optical absorption and accurate IR thermography, respectively. VACNTs are grown from lithographically defined catalyst and therefore allow for micrometer placement/sizing unlike paints or sputtered carbon. Third, the ability to design clusters of pixels with different photon absorptances to allow simultaneous images in selected energy bands of plasma radiation. Unlike metal foils, each pixel can have a custom thickness and composition of metal layers to determine spectral selectivity. As a result, the

^{a)}Author to whom correspondence should be addressed:
christopher.yung@nist.gov.

original concept of a pixelated imaging bolometer¹ can now be fully realized, and even extended, by using microfabrication techniques, unavailable 30 years ago.

B. Concept

We have developed a silicon microfabricated “multi-color” RGB imaging bolometer¹²⁻¹³ by customizing a pattern of individual neighboring pixels with different radiation absorption characteristics. For example, one pixel will absorb all wavelengths of light by utilizing VACNTs in combination with a thick high-Z metal layer. The next will have no VACNTs (thereby reflecting a large portion of UV-visible-IR light depending upon the spectral reflectance of the metal used) and a thick high-Z layer, and the third could have VACNTs and thin high-Z layer, so as to not stop the highest energy radiation from the plasma core. Features of this new concept include:

- A blackening layer of VACNTs with emissivity (ϵ) ≈ 1 and low thermal mass (2% of carbon).⁸
- Thousands of thermally decoupled mm-scale pixels can be fabricated on sensors with 10 cm x 10 cm active areas, resulting in improved spatial resolution without the need to solve for heat diffusion on each time-step.
- Pixels can be individually tailored to create an RGB sensor, according to the plasma temperature.
- An aperture mask can reduce the radiation load onto the IRIB allowing for accurate determination of each pixel’s local temperature rise (ΔT) relative to the surrounding silicon substrate.
- Each pixel is easily calibrated with a laser of known power and a radiometric grade MWIR camera, to obtain sensitivity (K/mW) and decay time (τ).

Fig.1 is a schematic of a composite RGB sensor for pinhole imaging of fusion plasmas. The RGB imaging bolometer is an assembly consisting of an aperture mask (gold) in front of a silicon microfabricated RGB IRIB.

II. FABRICATION

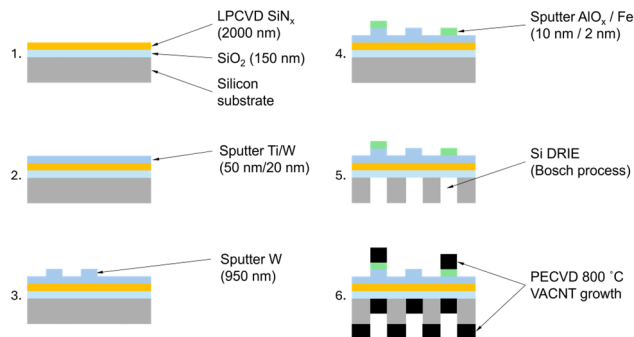


FIG. 2. Simplified process flow for the fabrication of an RGB IRIB with pixels individually defined with lift-off lithography.

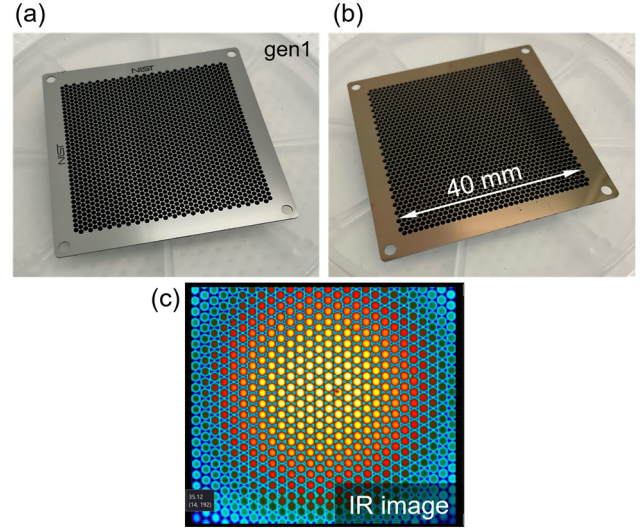


FIG. 3. (a) Plasma facing side of a mono-pixel IRIB (1569 pixels, 1 mm diameter, 1.075 mm pitch) with an active area of 40 mm x 40 mm (made from a 3-inch dia. silicon wafer). (b) IR camera facing side of the IRIB with VACNTs for IR imaging. (c) Flood illumination of the IRIB using a 500 lumen white LED source.

Fabrication of silicon microfabricated IRIBs uses standard processes of photolithography, physical vapor deposition (e-beam or sputtering), and dry etching (reactive ion etching (RIE)) to produce silicon nitride membrane suspended pixels with the desired thin film layers on top. Using multiple combinations of the preceding processes, one can easily define an IRIB with various pixel sizes and metal layer stacks across a single IRIB. A simplified process flow demonstrates the fabrication sequence in Fig. 2 for a three-color or RGB IRIB. Earlier generations of our detectors were mono-pixel designs whereby all pixels had identical layer stack-ups. The flexibility afforded by silicon microfabrication allows for easy fabrication of multi-pixel designs. This combinatorial flexibility is especially advantageous during IRIB development, allowing for multiple test regions on a single IRIB for different schemes/ideas/sizes all in a single fabrication run. The only non-standard process is a final high temperature growth of VACNTs at 800 °C which limits the materials available for use (e.g. refractory metals such as W are suitable while Au and Al are not). These process steps were used to develop three generations of IRIBs of increasing size and complexity (with the final version consisting of an aperture mask + RGB IRIB).

Standard 76.2-mm diameter or 150-mm diameter double-side polished silicon wafers are chosen as the substrate depending upon the final IRIB size desired. 76.2-mm (3-inch) diameter wafers were used for the square 40 mm x 40 mm sensor shown in Fig. 3, and 150-mm diameter silicon wafers were used for the 100 mm x 100 mm sensor shown in Fig. 4. Thermally oxidized wafers with a 150 nm SiO₂ layer, coated with low pressure chemical vapor deposition (LPCVD) low-stress (Si-rich) silicon nitride (stress < 100 MPa) defines the membrane support for the

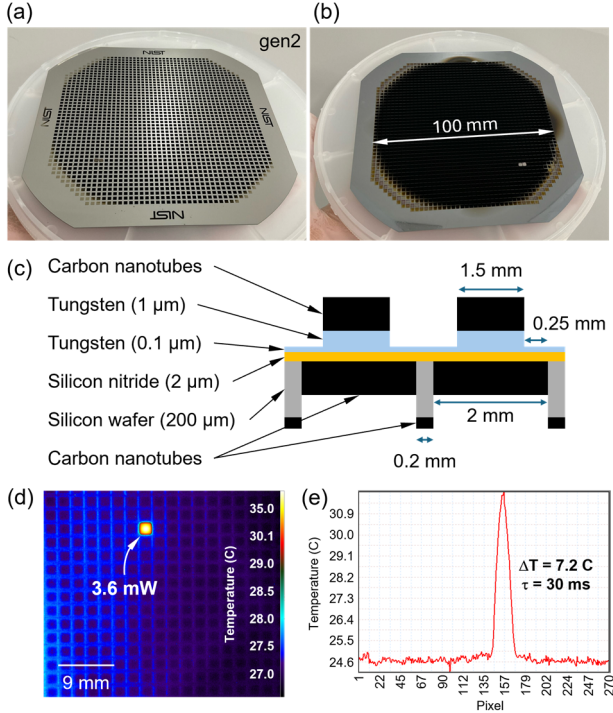


FIG. 4. (a) Plasma facing side of a mono-pixel IRIB (1968 square pixels, 2 mm x 2mm, 2.2 mm pitch) with an active area of 100 mm x 100 mm (made from a 150-mm dia. silicon wafer). (b) IR camera facing side of the IRIB with VACNTs for IR imaging. (c) Cross section view (not to scale) of the individual pixels. (d) IR camera image of the IRIB with a single pixel illuminated by a 405 nm laser diode with a measured power of 3.6 mW. (e) Line scan profile of the illuminated pixel showing a temperature rise of 7.2 °C, and a measured 1/e time constant of 30 ms (thermal time decay data and fit are not shown).

pixels. The SiO₂ and SiN_x layers are removed from one side of the wafer.

Next a 50 nm layer of Ti is sputtered on the SiN_x side followed by a 20 nm layer of W. These layers act as light blocking layers primarily for IR radiation emitted by the plasma walls. Both layers are chosen to be less than 100 nm to reduce their thermal conductivity to below bulk values.

Photolithography is performed to define the 1 μm thick W pixels. Photoresist is spin coated on the wafer and the pattern is exposed with a maskless aligner. W is sputtered onto the photoresist mask and lift-off is performed in acetone with ultrasonication to leave the remaining 1 μm thick W pixels. This lift-off process can be repeated any number of times by aligning to on-wafer fiducials allowing one to define varying layers of metals on the desired pixels. A final lift-off step (photolithography followed by deposition) is performed to define the pixels upon which VACNTs are to be grown. This is achieved by depositing a thin catalyst layer of 10 nm of AlO_x followed by 2 nm of Fe.

Backside processing of the wafer proceeds by spin coating photoresist on both sides of the wafer for protection of the metallized side and as an etch mask for silicon deep reactive ion etching (DRIE) of the backside. The backside

photoresist is exposed and developed exposing regions of silicon to be dry etched directly beneath each pixel thereby suspending each one on a silicon nitride membrane or drumhead. With an approximate Si DRIE etch rate of 3 μm / cycle, it takes approximately 30 minutes to etch through a 380 μm thick wafer (76.2 mm diameter) or 40 minutes to etch through a 500 μm thick wafer (150 mm diameter). The dry etch hardened photoresist is then subjected to an O₂ plasma for 5 minutes and removed in multiple acetone soaks, with a final rinse in isopropanol. At this point, the IRIB is separated from the surrounding silicon wafer and must be handled with care.

For VACNT growth on the plasma facing side, the IRIB is placed AlO_x/Fe catalyst side facing up on a substrate heater in a cold-wall plasma enhanced chemical vapor deposition (PECVD) system. The system ramps to 800 °C in an atmosphere of Ar and then switches to a mixture of C₂H₄/H₂/Ar with 1000 W of 2.45 GHz microwave power. Height of the VACNTs is linearly proportional to the growth time and is previously determined through test growths on representative samples (typically 5 to 15 minutes). Images of VACNTs grown on the plasma facing sides of first (gen1), second (gen2), and third (gen3) generation IRIBs are shown in Fig. 3(a), Fig. 4(a), and Fig. 5(a) respectively.

VACNT growth on the camera facing side of the IRIBs requires that an additional AlO_x/Fe catalyst layer be sputter deposited through a laser cut stencil mask onto the side with the deep etched silicon wells. The stencil mask confines the catalyst to the central region of the IRIB. For the final PECVD growth of VACNTs, the IRIB is placed silicon well side facing up with silicon spacers placed around the periphery to protect the VACNTs already present. VACNTs

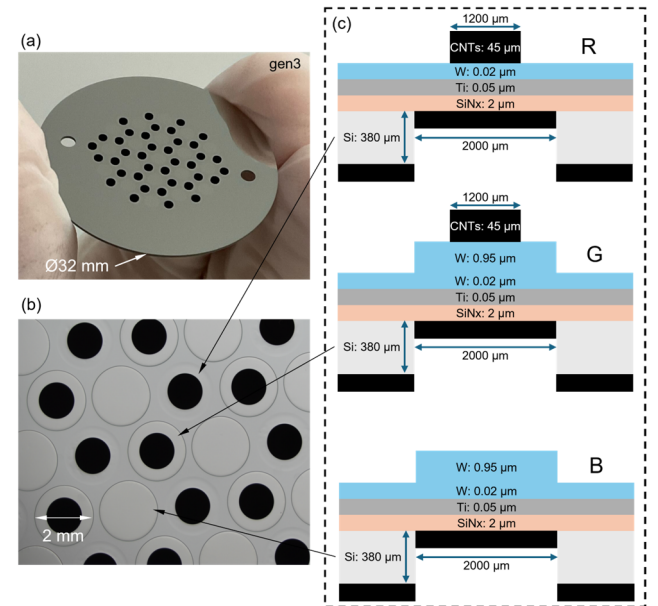


FIG. 5. (a) Plasma facing side of the RGB IRIB without the aperture. (b) Microscope image of the RGB pixels. (c) Cross section view (not to scale) of the individual pixels with arrows indicating their associated positions on the microscope image.

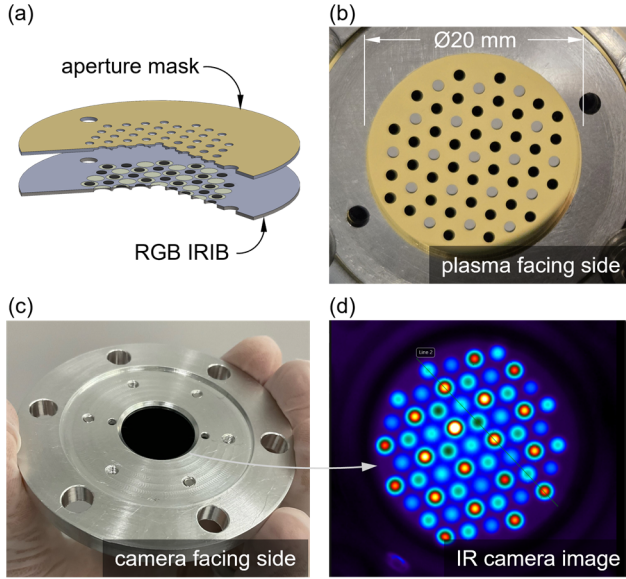


FIG. 6. (a) 3D CAD model of the composite RGB imaging bolometer consisting of a 100 nm Au-coated aperture mask (top) offset from an RGB IRIB (bottom). (b) Photograph of the plasma facing side of the aperture mask + RGB IRIB with an active area diameter of 20 mm. (c) Photograph of the IR camera facing side of the IRIB coated with VACNTs. The sensor is mounted in a custom machined DN40CF (ConFlat) aluminum flange. (d) IR camera image (VACNT side) of the sensor flood illuminated from the aperture side with a 500 lumen white LED source highlighting the response of the RGB pixels.

grown on the IR camera viewing side of gen1, gen2, and gen3 IRIBs are shown in Fig. 3(b), Fig. 4(b), and Fig. 6(c).

Fabrication of an aperture mask (Fig. 6(a)) proceeds in a similar fashion. Two separate photolithography and DRIE etch steps are performed to define aperture holes (1 mm dia.) for light entry and larger concentric counterbore regions to enclose the raised W+VACNT layer (2.050 mm dia.). 100 nm of Au is e-beam evaporated on the entrance aperture side to reflect ultraviolet to IR light.

Assembly of the composite IRIB sensor (aperture + RGB IRIB) is achieved by placing precision ground metal pins with a diameter of 1.990 mm in the two 2-mm diameter alignment holes deep etched (Si DRIE) into both pieces. A 25 μm thick annulus of laser cut Kapton is placed between the aperture and RGB IRIB as a compliant, thermally insulating layer. Laser cut annuli of pyrolytic graphite (50 μm thick) are placed on both sides of the composite IRIB to heat sink both the aperture and RGB IRIB to the metal vacuum flange.

An exploded cross-section view of the composite RGB sensor is pictured in Fig. 6(a) showing the aperture mask offset and aligned to the RGB IRIB. Fig. 6(b) is a photograph of the assembled aperture + RGB IRIB. A microscope picture in Fig. 5(b) shows the hexagonally close packed repeating pattern of the RGB pixels in detail. The silicon nitride membrane supporting each pixel is 2 mm in

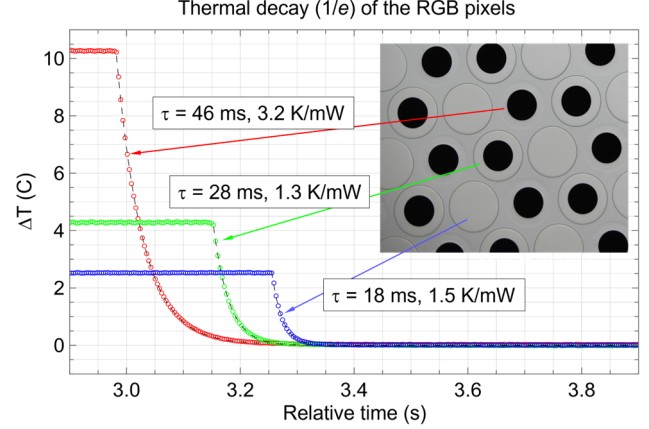


FIG. 7. Thermal time decay measurements in air of the three RGB pixels performed with a 3.2 mW, 405 nm laser diode focused down to a spot size < 1 mm diameter and measured with the FLIR IR camera. Dashed black lines are exponential decay fits to the data (open circles). Emissivity correction of the camera was set to $\epsilon = 1$ for the VACNTs. Inset is a microscope image with arrows indicating the associated thermal response of the measured RGB pixels.

diameter with a 2.2 mm pitch. Detailed cross sections (not to scale) of each of the RGB pixels are pictured in Fig. 5(c).

III. MEASUREMENT

A calibrated FLIR X8581 MWIR infrared camera with 100 mm lens and 512 Hz frame rate (~ 30 mK noise equivalent temperature difference) was used to observe the response (in air) of the fully-blackened side (Fig. 3(b), Fig. 4(b), Fig. 6(c)) of the sensors. For quantitative measurements of thermal time constant and sensitivity (K/mW) of individual pixels, the plasma-facing side (Fig. 3(a), Fig 4(a), Fig. 6(b)) was illuminated with a 405 nm diode laser (spot size less than 1 mm in diameter) pulse-biased with a 50% duty cycle 0.5 Hz square wave. A wide area 500-2000 lumen (uncalibrated) “tactical” LED flashlight was used for full field illumination (no pinhole) of the RGB IRIB for a qualitative demonstration of viewing a wide area source such as a plasma as shown in Fig. 6(d). A NIST calibrated Ophir Nova II laser power meter was used to check incident or reflected laser energies. Visible and scanning electron microscopes were used to inspect surface coatings. An example of the time response of the RGB prototype sensor is shown in Figure 7. We note that two of the pixels, in the pattern of three, are fully blackened with VACNTs, but the third one with uncoated tungsten has a measured reflectance at 405 nm of 47% and hence does not fully absorb the incident visible light. Interestingly, the thinnest one (most sensitive) has the longest decay time, due to effects of the silicon nitride “drumhead” dominating the heat capacity. Due to the relatively high thermal conductivity of the thick silicon substrate, each pixel is well isolated from its neighbor. The effects of making measurements in air versus in vacuum, are greatly reduced, compared to a classic thin foil (large area) IRVB, however

vacuum calibrations will be performed in the future. It is important that the IR camera has enough spatial resolution across the IRIB to resolve the local temperature of the substrate surrounding each pixel, as the ΔT of that pixel is relative to the substrate at the edge of the pixel. The use of the aperture mask (which is thermally decoupled from the sensor by the Kapton annulus) reduces this concern because the substrate essentially stays at one temperature, at least for short pulse experiments (10 seconds or less). For long plasma pulses, water cooling at the sensor and mask boundary is required.

IV. SUMMARY

A prototype multi-color IR imaging bolometer sensor has been demonstrated, using silicon microfabrication techniques, and tested (in air). The third-generation prototype also exhibits the possibility of including a silicon aperture mask, thermally decoupled from the underlying IRIB sensor to further isolate incident radiation to a known area on each pixel. Preventing incident radiation on the silicon between the pixels allows for more accurate ΔT measurements for each pixel. Unique features of this pixelated imaging bolometer include: a silicon nitride “drumhead” which supports each pixel and provides a controlled conducting path to the neighboring thick silicon substrate, VACNTs to provide near unity UV to IR absorption on the plasma facing side, and VACNTs as a high emissivity black-body re-emitter on the camera side of the sensor. Testing at a plasma facility later this year will be performed on the RGB IRIB to determine actual energy performance of the three different pixels. Because of the simple image processing, with no heat diffusion equation to be solved, our sensors should be useful for real-time feedback control of the plasma position by monitoring the edge plasma radiation, as recently demonstrated with standard IRVB foils at KSTAR.¹⁴

V. ACKNOWLEDGEMENTS

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VI. AUTHOR DECLARATIONS

A. Conflict of interest statement

A US patent has been applied for by G. A. Wurden and Los Alamos National Laboratory.¹²

A US patent has been applied for by C. S. Yung and the National Institute of Standards and Technology.¹³

B. Author contributions

Microfabrication of the sensors was performed by C. Yung at the Boulder MicroFab (BMF) NIST-Boulder. IR testing was performed by G. Wurden. Concepts and design iterations were jointly developed by C. Yung and G. Wurden unless otherwise noted in patent filings.

C. S. Yung: Conceptualization (equal), Formal Analysis (equal), Investigation (equal), Writing (equal).

G. A. Wurden: Conceptualization (equal), Formal Analysis (equal), Investigation (equal), Writing (equal).

VII. DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

VIII. REFERENCES

- ¹G. A. Wurden, US Patent 5861625A, “Imaging Bolometer”, 1997.
- ²G. A. Wurden, B. J. Peterson, and S. Sudo, *Rev. Sci. Instrum.* **68**, 766 (1997).
- ³G. A. Wurden, and B. J. Peterson, *Rev. Sci. Instrum.* **70**, 255 (1999).
- ⁴B. J. Peterson, *Rev. Sci. Instrum.* **71**, 3696 (2000).
- ⁵M. Itomi, B. J. Peterson, Y. Yamauchi, R. Sano, K. Mukai, and S. N. Pandya, *Plasma Fusion Res.* **9**, 3406080 (2014).
- ⁶F. Federici, J. J. Lovel, G. A. Wurden, B. J. Peterson, and K. Mukai, *Rev. Sci. Instrum.* **95**, 103525 (2024).
- ⁷G. A. Wurden, G. Partesotti, F. Reimold, K. Mukai, B. J. Peterson, and F. Federici, *Rev. Sci. Instrum.* **95**, 093503 (2024).
- ⁸N. A. Tomlin, *et al.*, *AIP Adv.* **10**, 055010 (2020).
- ⁹J. Lehman, C. Yung, N. Tomlin, D. Conklin, and M. Stephens, *Appl. Phys. Rev.* **5**, 011103 (2018).
- ¹⁰K. Mizuno, J. Ishii, H. Kishida, Y. Hayamizu, S. Yasuda, D. N. Futaba, M. Yumura, and K. Hata, *Proc. Natl. Acad. Sci. U.S.A.* **106**, 6044 (2009).
- ¹¹R. Fainchtein, D. M. Brown, K. M. Siegrist, A. H. Monica, E. Hwang, S. D. Milner, and C. C. Davis, *Phys. Rev. B* **85**, 125432 (2012).
- ¹²US patent pending by G. A. Wurden and Los Alamos National Laboratory (disclosed March 30, 2023, provisional #S167686.000, finalized Oct. 8, 2025, including the RGB concept).
- ¹³US patent pending by C. S. Yung and the National Institute of Standards and Technology (disclosed July 16, 2025, provisional # 63/959,405 filed on Jan. 13, 2026).
- ¹⁴C. S. Byun, S. Oh, S. K. Kim, B. S. Kim, Y. S. Han, S. H. Hahn, H. H. Lee, A. Jalalvand, Y. H. Lee, J. H. Hwang, R. Shousha, J. -S. Park and E. Kolemen, *Nucl. Fusion* **66**, 046021 (2026).