Light-concentrating microcone array for improving performance of infrared imaging devices

Boya Jin,[1] Aaron Brettin,[1] Grant W. Bidney,[1,2] Joshua M. Duran,[2] Gamini Ariyawansa,[2] Igor Anisimov,[2] Nicholaos I. Limberopoulos,[2] Augustine M. Urbas,[3] Kenneth W. Allen,[4] Sarath D. Gunapala,[5] and Vasily N. Astratov[1,2,*]

[1]Department of Physics and Optical Science, Center for Optoelectronics and Optical Communications, University of North Carolina at Charlotte, Charlotte, NC 28223-0001, USA
[2]Air Force Research Laboratory, Sensors Directorate, Wright Patterson AFB, OH 45433, USA
[3]Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson AFB, OH 45433, USA
[4]Advanced Concepts Laboratory, Georgia Tech Research Institute, Georgia Institute of Technology, Atlanta, GA 30332, USA
[5]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, California 91030, USA
**Tel: 1 (704) 687 8131, Fax: 1 (704) 687 8197, E-mail: astratov@uncc.edu*

NAECON 2021 - IEEE National Aerospace and Electronics Conference | 978-1-6654-4859-8/21/$31.00 ©2021 IEEE | DOI: 10.1109/NAECON49338.2021.9696394

***Abstract*— Light-harvesting low-index (*n*=1.6) microconical arrays are proposed for increasing the sensitivity and the signal-to-noise ratio (SNR) of mid-wave infrared (MWIR) focal plane arrays (FPAs) used in thermal cameras. Numerical modeling showed a 3-D Power enhancement factor ~ 50 in MWIR for 10° tapered microcones with D_t/D_b = 60 μm/8μm and *h*=150μm, where D_t and D_b are the top and bottom diameters of microcones, respectively. Such microconical arrays were fabricated in photoresist by using a nanoscribe tool directly on top of the front-illuminated Ni/Si Schottky-barrier, and three-fold enhancement in the photocurrent response was observed. The proposed approach permits increase of the SNR and the operation temperature of the MWIR imaging devices.**

Keywords—focal plane arrays, infrared imaging

I. Introduction

Since the 1960s, the design of non-imaging light concentrators was driven by the development of solar cells such as parabolic concentrators [1] and Köler integrators [2]. The design is based on geometrical optics, and it shows a fundamental tradeoff between the concentration factor (C), and the angle-of-view (AOV), α, in such structures which can be expressed as: $C=1/\sin^2\alpha$. [1,2]

Commercial micro-lens arrays used as light concentrators also showed the ability to increase pixels' sensitivity in the infrared (IR) photodetector focal plane arrays (FPAs). For this design, each photo-detecting pixel is aligned with a compact micro-lens, which allows reducing the individual pixel area and lowering the thermal noise level of the photodetector mesa consequently. The latter is important in mid-wave and long-wave IR (MWIR and LWIR) regimes, where the thermal noise limits the imaging quality of uncooled detectors. [3,4] It should be noted, however, that the AOV of such systems is limited due to long focal lengths (f) of the microlenses: α<arctan(d/2f), where d is the characteristic pixel size.

Such problem can be solved by using contact microlenses or metasurfaces such as high-index microspheres [5-7], integrated microlenses [8], metalenses [9-11], dielectric microdisk antenna arrays [12], and axilenses [13]. A sharper focusing can be achieved by those structures with shorter focal lengths. These structures can be integrated with photodetector FPAs, but their AOVs are still rather limited.

It has been suggested that the AOVs can be increased in curved FPAs. [14,15] Alternatively, coupling to pixels can be achieved by using flexible adiabatically tapered waveguides, [16,17] but the fabrication of such structures is rather difficult in practice.

A more practical approach to fabricate light-harvesting concentrator arrays [18] is based on using better established technologies such as anisotropic wet etching of Si. [19,20] The light can be resonantly trapped in high index (n~3.5) microcones that can be used for enhancing the quantum efficiency of Si-based photodetectors and for multispectral imaging with large AOV. [20]

In this work, we propose another possibility based on using arrays of low-index (n~1.6) microcones which can be fabricated in photoresist or plastic by using a nanoscribe or injection molding. We performed finite different time domain simulation in 2D to optimize the geometry parameters of such microcone structure and found the best predicted power enhancing ability in 3D for light-harvesting device. We also fabricated the optimized microcone array and measured the power enhancing ability of such array aligned with FPA.

II. Simulation and Experimental Results

Figure 1(a) shows the structure of the inverted low-index microcone as light-harvesting device. The plane wave will incident into the inverted microcone from the wider base and transmit to the smaller base of the cone, which is coupled to a photodetector. The power enhancement factor of the microcone, which determine the power collecting and delivering ability of light harvesting device, can be defined as

PEF = P_{cone}/P_0, where P_{cone} is the power collected by the detector with an inverted microcone equipped, and P_0 is the power collected by the same detector without the microcone above. There are four parameters to determine the geometry of the microcone, the top diameter D_t, the bottom diameter D_b, the height h, and the sidewall angle θ. In these four parameters, the fourth parameter will be automatically determined if any three of them is determined. In our simulation, the three parameters D_b, h, and θ is varied and the optimized geometry of the microcone structure is obtained to achieve highest power enhancement.

Figure 1(b) shows the fabrication method of low-index inverted microcone array. The microcone array is made by photoresist with a refractive index of n = 1.6. Using laser writing technology, any structure designed by computer software can be fabricated. In our experiment, we fabricated such microcone array by a commercial laser writing tool called nanoscribe.

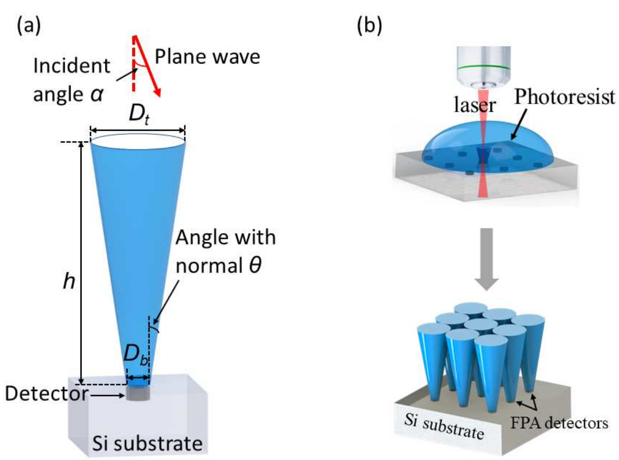

Figure 1 (a) Geometry of the inverted micorcone structure (b) the laser-writing Fabrication method of photoresist microcone array

We performed 2D finite different time domain numerical analysis of the light harvesting ability for a single wavelength λ=4 μm corresponding to the center of the MWIR range. We confirmed that based on our definition of power enhancement factor, the 3D results should be close to the square of 2D results. To optimize the geometry of the microcone to achieve best performance, the height h is varied from 10 μm to 150 μm, and the sidewall angle θ is varied from 5° to 30° when both the bottom diameter D_b and the size of photodetector mesa is set to be 8 μm. Figure 2(a) shows the power distribution map of light propagating through the microcone. The microcone structure performs as an adiabatically tapered waveguide, and the light is concentrated to a small compact beam on the photodetector mesa after passing through the mocrocone.

Figure 2(b) shows the power enhancement factor for different geometric parameters of the microcone. It is shown that to optimized the higher power enhancement factor, a higher height and smaller sidewall angle is preferred. In 2D results, the highest power enhancement factor of 7.2 times is obtained when the height of the cone is 150 μm with a 10° sidewall angle. This number indicates an ideal power enhancement factor of 50 times in 3D.

Figure 2(c) shows the angle-of-view (AOV) of the inverted microcone with bottom diameter of 8 μm, sidewall angle of 10° while the height is set to be 50 μm, 100 μm, and 150 μm for different incident angle and polarization. The AOV is defined as the incident angle where the power enhancement factor reduced to the half of the maximum value. It is shown that for the designed geometry of microcone, the AOV is around 15°, which is reasonable for a good detecting device.

Our experimental goals were to fabricate the proposed structures, integrate them with infrared FPAs, and demonstrate their ability to improve the photoresponse of the detectors with small mesa sizes. [5-7, 18-20] This would allow an increase in the SNR and, potentially, the operation temperature of the MWIR FPAs. [8] However, these tasks require fabrication of front-illuminated MWIR FPAs with small photodetector mesas (≤8 μm) and sufficiently large pitch (≥30 μm) which are not readily available.

To solve this problem, we turned to a technology of metal silicide/Si Schottky-barrier detectors [22,23] suitable for fabrication of front-illuminated MWIR FPAs with various mesa-to-pitch ratios. We fabricated front-illuminated SWIR Ni/Si Schottky-barrier photodetector FPA with 60 μm pitch and different photodetector mesa sizes: (a) full fill-factor with 58 μm aperture and (b) 22 μm aperture. The photodetectors were arranged as several 10×10 arrays on the same die. Within each array, all photodetectors were electrically connected in parallel to simplify the fabrication and testing.

We aimed at fabricating microcones with a bottom base of D_b = 8 μm, which is feasible for manufacture by using a nanoscribe, but still provide marked $PEF_{2\text{-}D}$ = 7.2 for h=150 μm and θ = 10°, form previous simulation results. They were fabricated on top of some of 22 μm aperture photodetector FPAs using a nanoscribe tool at the Air Force Research Laboratory (AFRL). First, a layer of photoresist with 150 μm thickness and small IR absorption was deposited on the surface of a front-illuminated FPA. Next, the photoresist was scanned by the focused laser causing the two-photon-induced polymerization. Meticulous micron-scale alignment of the microcones with the corresponding photodetector mesas was done. Finally, the unexposed parts of the photoresist were dissolved leaving behind the array of microcones with 60/8 μm top/bottom diameters, respectively. More detailed results about the power enhancement factor and AOV performance of microcones with bottom diameter D_b = 4 μm and D_b = 2 μm is also discussed [24].

Figure 3(a) shows a fast-speed fabrication and resulted in a layered structure of micorcones determined by the large distance between neighboring focusing planes through 3D laser scanning. Figure 3(b) showes a low-speed fabrication where we first exposed and polymerized the sidewall surface

Identify applicable funding agency here. If none, delete this text box.

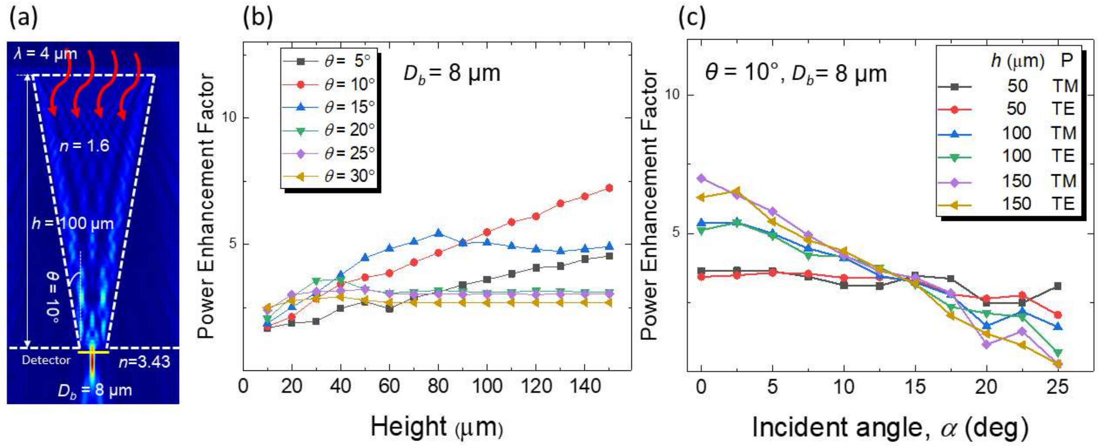

Figure 2 (a) power distribution map of light propagating through the microcone structure. (b) PEF for the microcone changing with a series of geometrical parameters. (c) AOV of microcone changing with different geometrical parameters at different incident angle and polarization.

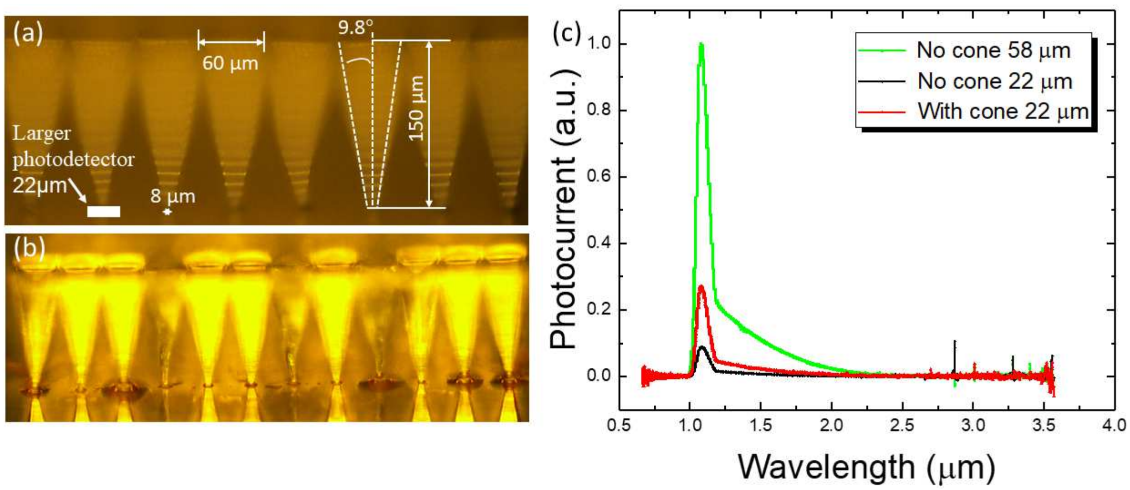

Figure 3 (a) Fast-speed fabrication of microcone array. (b) Low-speed fabrication of microcone array (c) Photocurrent response for 58 μm mesa without microcone, 22 μm mesa without microcone, and 22 μm mesa with microcone above.

of microcones. It is shown that half of the cones are good and can be used for measurement. Each microcone is aligned with a photodetector and the photocurrent in the detector is measured. Figure 3(c) shows a reduction in photocurrent signal when the photodetector mesa size decreases from 58 μm to 22 μm without microcone above, and an enhancement when the 22 μm mesa is equipped with a microcone. Since our calculated PEF values are normalized by the photoresponse of the same mesa without microcones, the larger mesa can be accounted by dividing $\mathrm{PEF}_{3\text{-D}} \sim 50$ estimated for 8 μm mesa by $(22/8)^2 \sim 7.56$. This allows for the maximal $\mathrm{PEF}_{3\text{-D}}$ to be estimated as ~ 6.6 for the 22 μm mesas.

III. CONCLUTION

We proposed application of low-index (n=1.6) microconical arrays for increasing the sensitivity and the SNR of FPAs used in MWIR cameras. In this approach, each microcone is considered as an imperfect tapered waveguide delivering light from its wider top base to its bottom base coupled to the photodetector mesa. It is shown that the maximal values of $\mathrm{PEF}_{3\text{-D}} \sim 50$ can be achieved for slightly tapered microcones (θ =10°) with sufficient height ($h \geq 120$ μm) at bottom base D_b = 8 μm. To demonstrate the proposed concept, the suboptimal microconical arrays with D_t/D_b = 60 μm/8 μm were fabricated by nanoscribe on top of the front-illuminated Ni/Si Schottky-barrier SWIR photodetectors with 22 μm mesas. Despite the fact that about half of the microcones were damaged due to imperfect fabrication, the three-fold enhancement in the photocurrent response was observed compared to the same FPA without microcones in a good agreement with our theoretical model.

The proposed microconical concentrators can be used for decreasing the size and the thermal noise of the photodetector mesas without sacrificing their photoresponse, thus increasing the SNR and the operation temperature of the imaging system. It can be particularly important in a MWIR regime where the thermal noise constitute one of the major factors limiting the quality of imaging by uncooled thermal cameras.

Acknowledgment

The authors are thankful to Drs. Daniel Fullager and Christopher Rosenbury for their help with fabrication of microconical arrays using a nanoscribe. This work was supported by Center for Metamaterials, an NSF I/U CRC, award number 1068050 and National Aeronautics and Space Administration (80NM0018D0004).

References

[1] R. Winston, J. C. Miñano, and P. Benítez, *Nonimaging Optics*, (Academic Press, 2004).

[2] J. C. Miñano, M. Hernández, P. Benítez, J. Blen, O. Dross, R. Mohedano, and A. Santamaría, "Free-form integrator array optics," Proc. SPIE **5942**, 59420C (2005).

[3] A. Rogalski, "Progress in focal plane array technologies," Prog. Quantum Electron. **36**(2-3), 342–473 (2012).

[4] C. L. Tan and H. Mohseni, "Emerging technologies for high performance infrared detectors," Nanophotonics **7**(1), 169–197 (2018).

[5] V. N. Astratov, K. W. Allen Jr., N. I. Limberopoulos, A. Urbas, and J. M. Duran, "Photodetector focal plane array systems and methods," U.S. patent 9,362,324 (7 June 2016).

[6] K. W. Allen, F. Abolmaali, J. M. Duran, G. Ariyawansa, N. I. Limberopoulos, A. M. Urbas, and V. N. Astratov, "Increasing sensitivity and angle-of-view of mid-wave infrared detectors by integration with dielectric microspheres," Appl. Phys. Lett. **108**(24), 241108 (2016).

[7] F. Abolmaali, A. Brettin, A. Green, N. I. Limberopoulos, A. M. Urbas, and V. N. Astratov, "Photonic jets for highly efficient mid-IR focal plane arrays with large angle-of-view," Opt. Express **25**(25), 31174–31185 (2017).

[8] A. Soibel, S. A. Keo, A. Fisher, C. J. Hill, E. Luong, D. Z. Ting, S. D. Gunapala, D. Lubyshev, Y. Qiu, J. M. Fastenau, and A. W. K. Liu, "High operating temperature nBn detector with monolithically integrated microlens," Appl. Phys. Lett. **112**(4), 041105 (2018).

[9] S. Zhang, A. Soibel, S. A. Keo, D. Wilson, S. B. Rafol, D. Z. Ting, A. She, S. D. Gunapala, and F. Capasso, "Solid-immersion metalenses for infrared focal plane arrays," Appl. Phys. Lett. **113**(11), 111104 (2018).

[10] Li, J. Deng, J. Zhou, Z. Chu, Y. Yu, X. Dai, H. Guo, L. Chen, S. Guo, M. Lan, and X. Chen, "HgCdTe mid-Infrared photo response enhanced by monolithically integrated meta-lenses," Sci. Rep. 10(1), 6372 (2020).

[11] E. Mikheeva, J.-B. Claude, M. Salomoni, J. Wenger, J. Lumeau, R. Abdeddaim, A. Ficorella, A. Gola, G. Paternoster, M. Paganoni, E. Auffray, P. Lecoq, and S. Enoch, "CMOS-compatible all-dielectric metalens for improving pixel photodetector arrays," APL Photon. 5, 116105 (2020).

[12] A. Kazemi, Q. Shu, V. Dahiya, Z. Taghipour, P. Paradis, C. Ball, T. J. Ronningen, S. Zollner, S. M. Young, J. Budhu, K. A. Grossklaus, T. E. Vandervelde, A. Grbic, and S. Krishna, "Subwavelength antimonide infrared detector coupled with dielectric resonator antenna," Proc. SPIE **11002**, 1100221 (2019).

[13] Y. Chen, W. A. Britton, and Luca Dal Negro, "Design of infrared microspectrometer based on phase-modulated axilenses,"App. Optics **59**, 5532 (2020).

[14] S.-B. Rim, P. B. Catrysse, R. Dinyari, K. Huang and P. Peumans, "The optical advantages of curved focal plane arrays," Opt. Express **16**, 4965-4971 (2008).

[15] Y. Zhai, Q. Han, J. Niu, J. Liu, and B. Yang, "Microfabrication of bioinspired curved artificial compound eyes: a review," Microsystem Technologies (2020).

[16] https://doi.org/10.1007/s00542-020-05090-3(0123456789

[17] V. N. Astratov, A. Brettin, N. I. Limberopoulos, and A. Urbas, "Photodetector Focal Plane Array systems and methods based on microcomponents with arbitrary shapes," U.S. patent 10,585,238 (March 10, 2020).

[19] B. Jin, G.W. Bidney, A. Brettin, N.I. Limberopoulos, I. Anisimov, A.M. Urbas, H. Li, and V.N. Astratov, "High-index micro-cones for focusing and concentrating light in MWIR focal plane arrays," Proc. of *IEEE Aerospace and Electronics Conference–NAECON* (IEEE, 2019), pp. 665–668.

[20] B. Jin, G.W. Bidney, A. Brettin, N.I. Limberopoulos, J.M. Duran, G. Ariyawansa, I. Anisimov, A.M. Urbas, S.D. Gunapala, H. Li, and V.N. Astratov, "Microconical silicon mid-IR concentrators: spectral, angular and polarization response," Opt. Express **28**, 27615- 27627 (2020).

[21] A. Brettin, N. I. Limberopoulos, I. Anisimov, A. M. Urbas, and V. N. Astratov, "Microconical arrays as novel light-concentrating structures for enhancing sensitivity, angle-of-view, and reducing dark current of mid-IR FPAs," Proc. of *IEEE Aerospace and Electronics Conference–NAECON* (IEEE, 2018), pp. 496–498.

[22] F. Shepherd and A. Yang, "Silicon Schottky retinas for infrared imaging," IEDM Tech. Dig. **1973**, 310–313 (1973).

[23] F. D. Shepherd, "Schottky diode based infrared sensors," Proc. SPIE **0443**, 42–49 (1983).

[24] B. Jin, A. Brettin, G. W. Bidney, N. I. Limberopoulos, J. M. Duran, G. Ariyawansa, I. Anisimov, A. M. Urbas, K. W. Allen, S. D. Gunapala, and V. N. Astratov, "Light-harvesting microconical arrays for enhancing infrared imaging devices: Proposal and demonstration," Appl. Phys. Lett. **119**, 051104 (2021).