Journal of ELECTRICAL ENGINEERING, VOL 73(2022), NO3, 203–208

sciendo

PAPERS

Pixel level vacuum packaging for single layer microbolometer detectors with on pixel lens

M. Yusuf Tanrikulu

This paper presents a new approach for fabrication of single layer microbolometer detectors featuring pixel level vacuum packaging together with a lens on the pixel. The proposed lens structure can be used to increase the fill factor of the detector so that the pixel size can be decreased without decreasing the minimum feature size in the detector which is a problem in single layer microbolometers. The designs of the lens and the fabrication process of pixel level vacuum packaged microbolometer detector together with this lens are given in the framework of this study. The optical and mechanical simulations of the structure are performed. The radius of curvature of the lens is optimized to be $25\,\mu$m and it is shown that the condensing efficiency is $100\,\%$ for $3\,\mu$m lens-detector distance. The deflection in the lens structure is found approximately as 0.8 nm in 1 atm environment pressure, showing that the proposed structure is durable. The proposed structure increases the fill factor to twice of the original value without decreasing the minimum feature size in the fabrication processes, resulting in the same amount of improvement in the performance of the detector. This approach can also be used to increase the yield and decrease the fabrication cost of single layer and also standard microbolometers with small pixel sizes, as it integrates the vacuum packaging in the fabrication steps.

K e y w o r d s: pixel level packaging, lens on pixel, single layer microbolometer

1 Introduction

Uncooled infrared detectors have been widely used for a long period of time due to their various advantages when compared with the quantum detectors. These advantages include the room temperature operation, monolithic fabrication on CMOS readout circuits, having low weight, dissipating low power, and operation on large spectral range like 8–12 μm. Beside these technical advantages, having a low cost makes uncooled detectors suitable for civilian and commercial applications like night vision for automotive, security, firefighting, and marine applications [1].

Microbolometers are composed of an active layer with high temperature coefficient of resistance (TCR) providing a change in its resistance due to absorbed infrared radiation, support arms which provide both electrical and mechanical connections, and an absorbing layer which collects the infrared radiation. Generally different materials are used for these layers to increase the performance of the detectors. Vanadium oxide (VO_x) and amorphous silicon (a-Si) are the mostly used active detector materials in microbolometers [2–5], while silicon nitride (Si_3N_4) is generally used as absorber layer [6, 7]. This multi layer structure increases the design and fabrication complexity and dependently increases the cost of the detector. For this reason, using the same material as absorber, active layer, and structural layer and building a single layer detector is started to be studied to obtain cost effective solutions. A single layer microbolometer approach was realized using platinum film having a thickness of 7 nm with a TCR value of 0.14 %/K [8]. Another realization was made using ALD coated ZnO thin film with a TCR value of −10.4 %/K which is much higher than the TCR of mostly used materials [9].

Microbolometers are most widely used uncooled infrared detectors due to its respectable performance, small pixel size, and easy fabrication [10]. There is a tremendous effort to reduce the pixel size of microbolometer detectors to decrease the unit cost. There are focal plane arrays with 10 μm pixel pitch available at the market [11], while there are studies to decrease the pitch down to 6 μm using nanotubes [12]. Decreasing the pixel size can reduce the unit cost, but the need for high process capabilities with expensive lithography equipment for fabrication of small sized pixels prevents the reduction in the cost. Furthermore, the fabrication processes of single layer microbolometers limit the decrease in minimum feature size even high process capabilities are available.

Another parameter that affects the cost of the imaging systems is the packaging of detectors. Since the detectors operate at vacuum conditions to have high performance, the cost of vacuum packaging should be decreased as much as possible. There are several vacuum packaging methods reported including die level packaging [13–16] and wafer level packaging [17–22]. There are also efforts to make pixel level vacuum packaging where the packaging process is the part of detector fabrication process [23–32]. By this method, the need for expensive packaging equipment like a wafer bonder can be eliminated. There are

Department of Electrical-Electronics Engineering, Adana Alparslan Turkes Science and Technology University, Adana, Turkey, Metu Mems Center, Middle East Technical University, Ankara, Turkey, mytanrikulu@atu.edu.tr, Orcid: 0000-0001-7956-1289

https://doi.org/10.2478/jee-2022-0027, Print (till 2015) ISSN 1335-3632, On-line ISSN 1339-309X

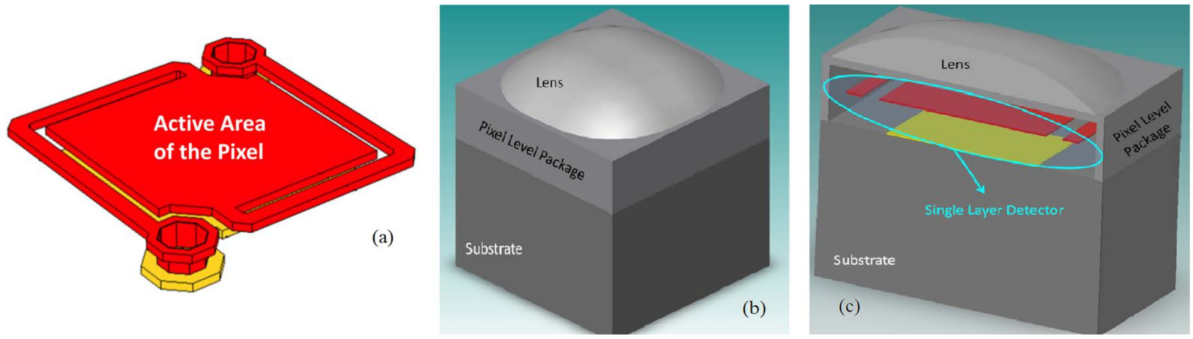

Fig. 1. 3D views of the single layer detector structure and the proposed pixel level vacuum packaged detector together with a lens on the pixel: (a) – single layer detector structure which is used from the study Tanrikulu *et al* [9], (b) – the whole structure, and (c) – the cross-sectional view

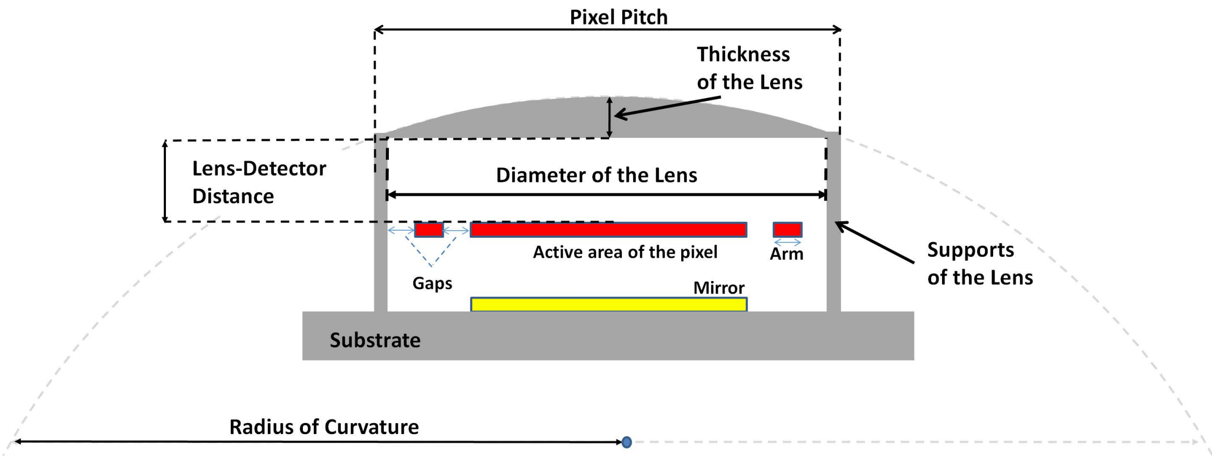

Fig. 2. The cross-sectional view with the dimension definitions and important parameters used for the design of the proposed structure and the lens. Radius of curvature and lens thickness together with lens-detector distance are the important parameters to be simulated in order to optimize the condensing efficiency of the lens

studies to form a lens on each individual pixel in both visible and infrared imaging applications [33–35]. But these studies do not have pixel level vacuum packaging solutions, so they still need expensive packaging equipment.

This study proposes a new fabrication approach for single layer microbolometer detectors including pixel level packaging together with a lens on pixel. The designs of the lens and fabrication flow of the proposed structure are given in detail. The lens is simulated with RayOptics Module of COMSOL software to see the condensing efficiency, and the whole structure is mechanically simulated using CoventorWare FEM tool to see the deflection in the lens. This approach can be used to fabricate small sized single layer or standard microbolometer pixels without the need for high process capabilities, since the proposed lens structure prevents the decrease in the fill factor of the detector. Furthermore, an increase in yield is possible since the vacuum packaging is performed as a part of detector fabrication process. To author's knowledge, this structure is the first of its type in literature combining pixel level packaging with a lens in small sized uncooled infrared microbolometers.

2 Design of the lens

Figure 1 shows the 3D view of the single layer detector structure and the proposed pixel level vacuum packaged detector together with a lens on the pixel. The single layer detector structure is used from the study by Tanrikulu *et al* [9].

Figure 2 shows the cross-section of the structure with the dimension definitions and important parameters used for the design of the proposed structure and the lens. The minimum feature size is taken as $1\,\mu$m as proposed in Tanrikulu *et al* [9], so the gaps and arms are $1\,\mu$m wide, while the pixel pitch (PP) is reduced to $17\,\mu$m to have a small sized pixel. As a result, the active area of the pixel is $10\,\mu\text{m} \times 10\,\mu$m making a fill factor of 35 % without the lens (fill factor is the ratio of the active area to the total detector area). Radius of curvature and lens thickness together with lens-detector distance are the important parameters to be simulated to optimize the condensing efficiency of the lens.

As can be seen figure the plano-convex lens is chosen because it can be easily fabricated when compared to other type of converging lenses like positive-meniscus.

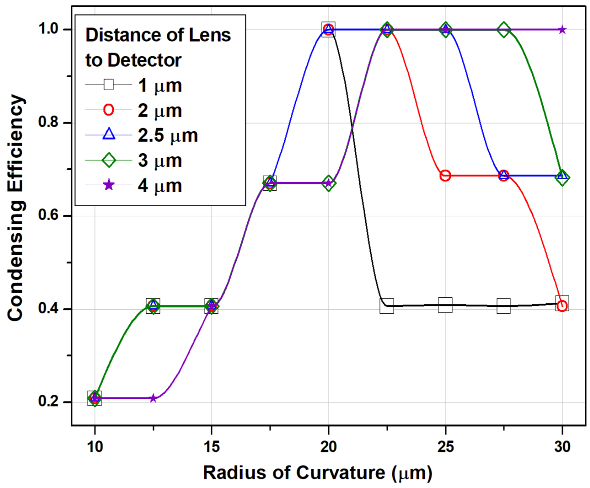

Fig. 3. Condensing efficiency of the lens with respect to radius of curvature and lens-detector distance. Radius of curvature and lens-detector distance are chosen as 25 μm and 3 μm, respectively

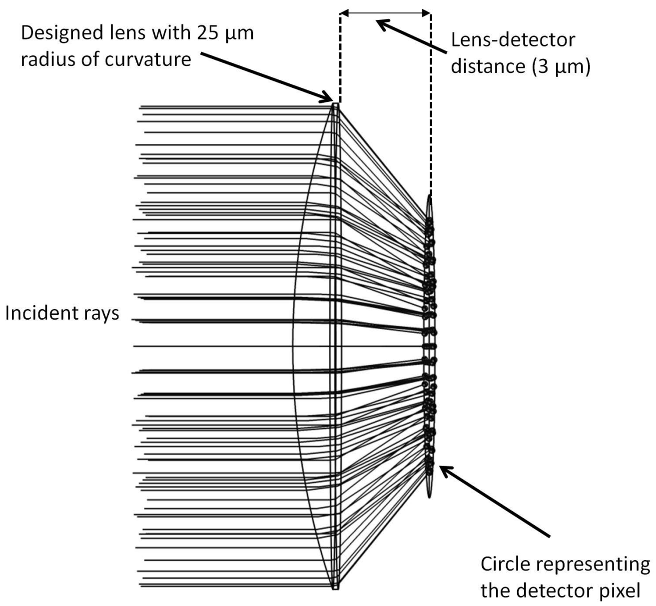

Fig. 4. The results of the ray tracing simulations with the optimized structure dimensions. As can be seen all the incoming rays arrive on the circle representing the detector pixel

In positive meniscus lens the focal length becomes very large, since the difference between the radiuses of curvature of two surfaces is small, so the incident radiation cannot be focused to proper area. The diameter of the lens is 16 μm, since the lens of the next pixel should be 1 μm away, which is the minimum feature size.

The thickness of the lens can be found by simple geometrical calculations using the radius of curvature of the lens as

$$d = R - \sqrt{R^2 - \left(\frac{P_P}{2}\right)^2}, \qquad (1)$$

where R is the radius of the curvature and P_P is the pixel pitch.

The focal length of the plano-convex lens is calculated from Lens Maker's Equation as [36]

$$f = \frac{R}{n-1}, \qquad (2)$$

where n is the refractive index of the lens material.

The lens material is chosen as a-Si since its fabrication process is compatible with the previous process steps of the proposed structure (see next section) and CMOS process, as the deposition temperature is not very high. Furthermore, the extinction coefficient of a-Si is zero [37] like that of bulk silicon [38] making it transparent in the 8–12 μm wavelength range. Therefore, a suitable antireflection coating like titanium nitride (TiN) will be sufficient for the lens to have approximately 100 % transmission. The refractive index of a-Si is taken as 3.42 during the parameter calculations and simulations of the lens [37].

The other important parameter is the ratio of the energy arriving on the microbolometer pixel to the ratio of energy incident on the whole structure, namely the condensing efficiency of the lens. The infrared rays incident on the structure may not reach the microbolometer depending on the lens thickness (due to high refraction amount of the rays) and the distance of the detector to the lens (due to focusing properties). To optimize the lens thickness and the distance of the detector to the lens, the structure is simulated using the RayOptics module of COMSOL software. During the simulations the detector pixel is represented by a circle having a diameter of 10 μm which is same as pitch of the active area. The radius of curvature of the lens is changed between 10 μm and 30 μm and the distance of the microbolometer pixel is changed between 1 μm and 4 μm. Figure 3 shows the condensing efficiency with respect to radius of curvature and the distance of the lens to the pixel. From the simulations the radius of curvature and the lens-detector distance are chosen as 25 μm and 3 μm respectively, to have 100 % condensing efficiency. The values are selected such that small changes in the targeted dimensions do not affect the efficiency and the lens thickness does not increase much. The thickness of the lens can be calculated as 1.5 μm using Equation 1. Figure 4 shows the results of the ray tracing simulations with the optimized radius of curvature and lens-detector distance. All the incoming rays arrive on the circle representing the detector pixel.

3 Design of fabrication process flow

Figure 5 shows the designed fabrication process flow that can be used to fabricate the proposed structure in Fig. 1. The process flow of the single layer detector is same as the study by Tanrikulu *et al* [9] except the removal of sacrificial layer step, so the details are not shown here, Fig. 5(a). The process continues with the coating of second sacrificial layer which is polyimide and etching of both sacrificial layers are performed for the formation of

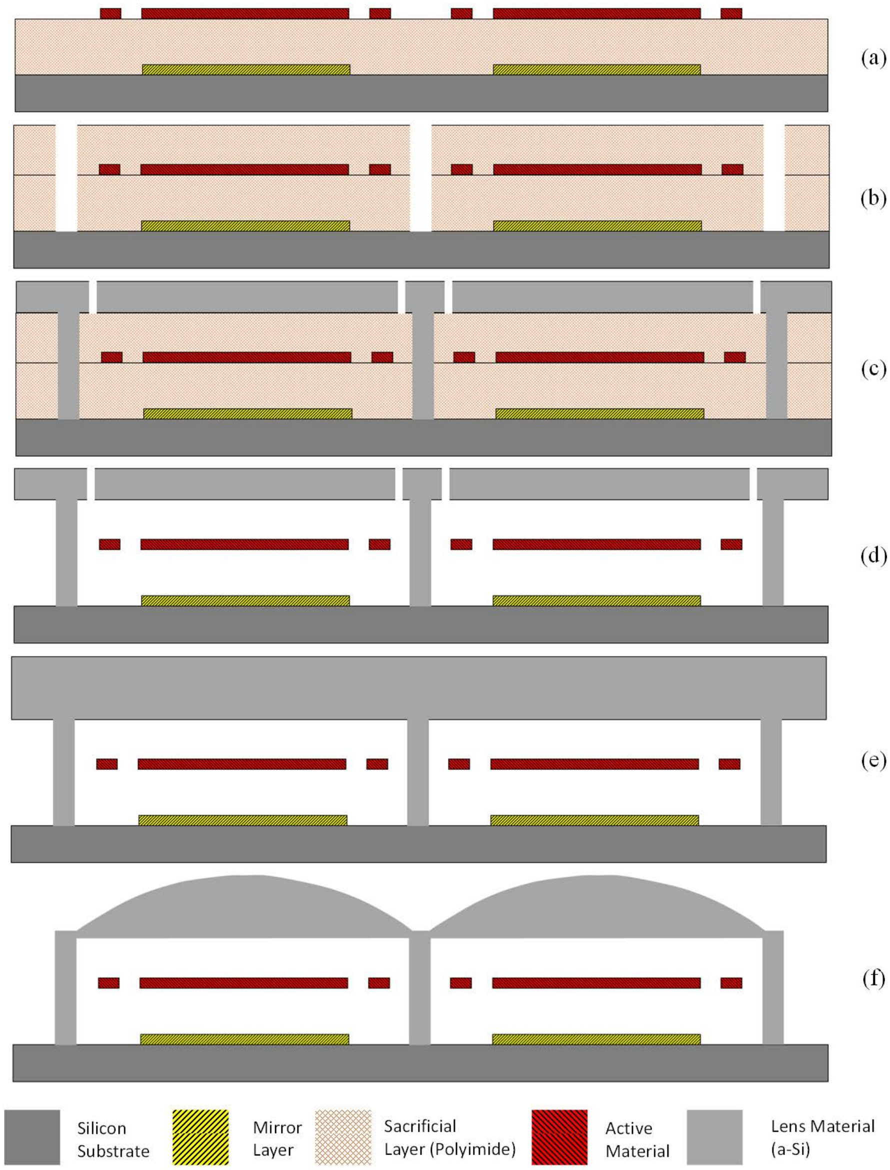

Fig. 5. The designed fabrication process flow. (a) single layer microbolometer on the sacrificial layer (polyimide), (b) coating of second sacrificial layer and etching of lens supports, (c) deposition of first part of lens material (a-Si) and etching of exhaust holes, (d) etching of sacrificial layers, (e) deposition of second part of lens material under vacuum, and (f) formation of lens with grayscale lithography

lens supports, Fig. 5(b). The lens material, which is chosen as a-Si, is deposited to fill the etched regions to form the lens support and the first part of the lens, and this layer is etched to form the exhaust holes, Fig. 5(c). These holes are used to etch the sacrificial layers in the next step, Fig. 5(d). Another a-Si layer is deposited to fill the exhaust holes and form the second part of the lens, Fig. 5(e). This material can be coated using sputtering technique under vacuum, so the detectors will stay in vacuum environment which is required for high performance. Furthermore, the deposition temperature is less than 300 °C, which is a suitable temperature for the previous process steps and CMOS fabrication process in case the structure is fabricated on a CMOS readout circuit. The dome shape of the lens can be obtained using grayscale lithography technique as in [39, 40] as the last step of the process Fig. 5(f). An antireflection coating, like TiN, can be deposited before the formation of the lens if needed, and the grayscale lithography technique can be applied to antireflection coating and lens together.

4 Mechanical simulations of the structure

The mechanical stiffness of the structure is important since it can affect the design parameters. A deflection can occur in the lens [28] and the lens can become useless if too much deflection occurs. To see the deflection amount of the lens, the proposed structure is mechanically simulated using Coventorware FEM simulation tool. During the simulations it is assumed that 1 atm air pressure exist in the environment. Figure 6 shows the results of the simulation. According to the results, the designed lens has a maximum deflection of approximately 0.8 nm which is an acceptable value when the total lens thickness is considered. The simulation results show that the proposed

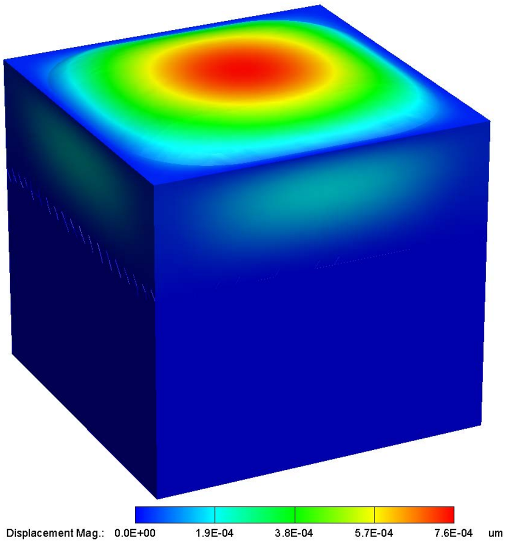

Fig. 6. The result of the mechanical simulation. The maximum deflection of the lens is approximately 0.8 nm which is an acceptable value showing that the proposed structure together with the lens is durable

structure together with the lens is durable with the designed parameters.

5 Conclusion

This study proposes a new fabrication approach for single layer microbolometer detectors including pixel level packaging together with a lens on pixel. The designs of the lens and fabrication flow of the proposed structure are given in detail. The lens is optically simulated using RayOptics module of COMSOL software to optimize the condensing efficiency and lens dimensions. The structure is mechanically simulated using CoventorWare FEM tool to see the deflection in the lens. It is shown by the simulations that the lens will have 100 % condensing efficiency for 25 μm radius of curvature and 3 μm lens-detector distance. The proposed structure is mechanically stable since the simulated value of 0.8 nm is an acceptable amount of deflection in the lens. This approach can be used to fabricate small sized single layer and standard microbolometer pixels without the need for high process capabilities since the proposed lens structure prevents the decrease in the fill factor of the detector. Furthermore, an increase in yield is possible since the vacuum packaging is performed as a part of detector fabrication process. The process flow can be modified to include photoresist reflow or melting as suggested in [41] in a future study if grayscale lithography process is needed to be avoided.

References

[1] Yole Developpement "Thermal Imagers and Detectors", *Market and Technology Report*, https://s3.i-micronews.com/uploads/2020/11/YDR20133b-Thermal-Imagers-and-Detectors-2020-Sample.pdf.

[2] A. Voshell, N. Dhar, and M. M. Rana, "Materials for microbolometers: vanadium oxide or silicon derivatives", *Image Sensing Technologies: Materials, Devices, Systems, and Applications IV*, p. 102090M, 2017, https://doi.org/10.1117/12.2263999.

[3] A. Rogalski, P. Martyniuk, and M. Kopytko, "Challenges of small-pixel infrared detectors: A review", *Reports on Progress in Physics*, vol. 79, no. 4, p. 46501, 2016, https://doi.org/10.1088/0034-4885/79/4/046501.

[4] D. D. Bruyker and B. Xu, "Fabrication of vanadium oxide microbolometers on thin polyimide films", *Transducers and Eurosensors XXVII: The 17th International Conference on Solid-State Sensors, Actuators and Microsystems*, pp. 62–65, 2013, https://doi.org/10.1109/Transducers.2013.6626701.

[5] S. K. Ajmera, A. J. Syllaios, G. S. Tyber, M. F. Taylor, and R. E. Hollingsworth, "Amorphous silicon thin-films for uncooled infrared microbolometer sensors", *Infrared Technology and Applications XXXVI*, p. 766012, 2010, https://doi.org/10.1117/12.850545.

[6] A. G. U. Perera, *Bolometers*, Rijeka, Crotia: InTech, 2012, https://doi.org/10.5772/33000.

[7] R. Ambrosio, M. Moreno, J. Mireles, A. Torres, A. Kosarev, and A. Heredia, "An overview of uncooled infrared sensors technology based on amorphous silicon and silicon germanium alloys", *Physica Status Solidi (C) Current Topics in Solid State Physics*, vol. 7, no. 3-4, pp. 1180–1183, 2010, https://doi.org/10.1002/pssc.200982781..

[8] S. Yoneoka *et al*, "ALD-metal uncooled bolometer", *Proceedings of the IEEE International Conference on Micro Electro Mechanical Systems (MEMS)*, pp. 676–679, 2011, https://doi.org/10.1109/MEMSYS.2011.5734515.

[9] M. Y. Tanrikulu, . Yildizak, A. K. Okyay, O. Akar, A. Sara, and T. Akin, "Realization of Single Layer Microbolometer Detector Pixel Using ZnO Material", *IEEE Sensors Journal*, vol. 20, no. 17, pp. 9677–9684, 2020, https://doi.org/10.1109/JSEN.2020.2992991.

[10] L. Yu, Y. Guo, H. Zhu, M. Luo, P. Han, and X. Ji, "Low-cost microbolometer type infrared detectors", *Micromachines (Basel)*, vol. 11, no. 9, 2020, https://doi.org/10.3390/MI11090800.

[11] Leonardo DRS, "Tenum 640 Thermal Camera Cores", https://www.leonardodrs.com/commercial-infrared/products/uncooled-camera-modules/tenum-640/(accessed Mar 29), 2021.

[12] M. Michel *et al*, "Scalable nanotube-microbolometer technology with pixel pitches from 12 down to 6 μm", *Electro-Optical and Infrared Systems: Technology and Applications XVII*, p. 1153704, Sep 2020, https://doi.org/10.1117/12.2573895.

[13] Z. Gan, D. Huang, X. Wang, D. Lin, and S. Liu, "Getter free vacuum packaging for MEMS", *Sensors and Actuators, A: Physical*, vol. 149, no. 1, pp. 159-164, 2009, https://doi.org/10.1016/j.sna.2008.10.014.

[14] H. Hata *et al*, "Uncooled IRFPA with chip scale vacuum package", *Infrared Technology and Applications XXXII*, p. 620619, 2006, https://doi.org/10.1117/12.673072.

[15] T. Ito, T. Tokuda, M. Kimata, H. Abe, and N. Tokashiki, "Vacuum packaging technology for mass production of uncooled IRFPAs", *Infrared Technology and Applications XXXV*, p. 72982A, 2009, https://doi.org/10.1117/12.822707.

[16] M. Kimata, M. T. Tokuda, A. Tsuchinaga, T. Matsumura, H. Abe, and N. Tokashiki, "Vacuum packaging technology for uncooled infrared sensor", *IEEJ Transactions on Electrical and Electronic Engineering*, vol. 5, no. 2, pp. 175–180, 2010, https://doi.org/10.1002/tee.20514.

[17] J. F. Brady III, *et al*, "Advances in amorphous silicon uncooled IR systems", *Infrared Technology and Applications XXV*, p. 161, 1999, https://doi.org/10.1117/12.354517.

[18] R. Gooch and T. Schimert, "Low-cost wafer-level vacuum packaging for MEMS", *MRS Bulletin*, vol. 28, no. 1, pp. 55–59, 2003, https://doi.org/10.1557/mrs2003.18.

[19] A. Hilton and D. S. Temple, "Wafer-level vacuum packaging of smart sensors", *Sensors (Switzerland)*, vol. 16, 2016, https://doi.org/10.3390/s16111819.

[20] A. Kennedy *et al*, "Advanced uncooled sensor product development", *Infrared Technology and Applications XLI*, p. 94511C, 2015, https://doi.org/10.1117/12.2177462.

[21] C. Li *et al*, "Low-cost uncooled VO x infrared camera development", *Infrared Technology and Applications XXXIX*, p. 87041L, 2013, https://doi.org/10.1117/12.2019653.

[22] L. Sengupta *et al*, "BAE systems' SMART chip camera FPA development", *Infrared Technology and Applications XLI*, p. 94511B, 2015, https://doi.org/10.1117/12.2177011.

[23] A. Astier, A. Arnaud, J.-L. Ouvrier-Buffet, J.-J. Yon, and E. Mottin, "Advanced packaging development for very low cost uncooled IRFPA", *Infrared Technology and Applications XXX*, p. 412, 2004, https://doi.org/10.1117/12.544122.

[24] E. Bercier, P. Robert, D. Pochic, J. L. Tissot, A. Arnaud, and J. J. Yon, "Far Infrared Imaging Sensor for mass production of Night Vision and Pedestrian Detection Systems", *Advanced Microsystems for Automotive Applications: Smart Systems for Safe, Sustainable and Networked Vehicles*, pp. 301–312, 2012, https://doi.org/10.1007/978-3-642-29673-4_28.

[25] D. P. Butler and Z. Celik-Butler, "A Device-Level Vacuum-Packaging Scheme for Microbolometers on Rigid and Flexible Substrates", *IEEE Sensors Journal*, vol. 7, pp. 1012–1019, 2007, https://doi.org/10.1109/JSEN.2007.896560.

[26] G. Dumont *et al*, "Pixel level packaging for uncooled IRFPA", *Infrared Technology and Applications XXXVII*, p. 80121I, 2011, https://doi.org/10.1117/12.883852.

[27] G. Dumontet *et al*, "Current progress on pixel level packaging for uncooled IRFPA", *Infrared Technology and Applications XXXVIII*, pp. 83531I–83531I-8, 2012, https://doi.org/10.1117/12.919918.

[28] K. Ikushima, A. Baba, M. Kyougoku, K. Sawada, and M. Ishida, "Fabrication and characterization of a pixel level micro vacuum package for infrared imager", *Proceedings of the IEEE International Conference on Micro Electro Mechanical Systems (MEMS)*, pp. 520–523, 2004, https://doi.org/10.1109/mems.2004.1290636.

[29] G. J. Jeon, W. Y. Kim, and H. C. Lee, "Thin-film vacuum packaging based on porous anodic alumina (PAA) for infrared (IR) detection", *Proceedings of IEEE Sensors*, pp. 3–6, 2012, https://doi.org/10.1109/ICSENS.2012.6411110.

[30] W. Rabaud, *et al*, "Recent development in pixel level packaging for uncooled IRFPA", *Electro-Optical and Infrared Systems: Technology and Applications VII*, p. 78340T, 2010, https://doi.org/10.1117/12.868462.

[31] J. L. Tissot, P. Robert, A. Durand, S. Tinnes, E. Bercier, and A. Crastes, "Status of uncooled infrared detector technology at ULIS, France", *Defence Science Journal*, vol. 63, no. 6, pp. 545–549, 2013, https://doi.org/10.14429/dsj.63.5753.

[32] J. J. Yon *et al*, "Latest improvements in microbolometer thin film packaging: paving the way for low-cost consumer applications", *Infrared Technology and Applications XL*, p. 90701N, 2014, https://doi.org/10.1117/12.2050378.

[33] U. C. Boettiger and J. Li, "Controlling Lens Shape in a Microlens Array", *US 7, 218, 452 B2*, 2007.

[34] A. Piehl, J. R. Przybyla, A. L. Ghozeil, and E. T. Martin, "Self-Packaged Optical Interference Display Device Having Anti-Stiction Bumps, Integral Micro-Lens, and Reflection-Absorbing Layers", *US, 7, 370, 185 B2*, 2008.

[35] T. R. Schimert, T. P. Fagan, and A. J. Syllaios, "Pixel-Level Optical Elements for Uncooled Infrared Detector Devices", *US 8, 610, 070 B2*, 2013.

[36] E. Hecht, *Optics*, 4th ed. San Francisco: Addison-Wesley, 2002.

[37] D. T. Pierce and W. E. Spicer, "Electronic structure of amorphous Si from photoemission and optical studies", *Physical Review B*, vol. 5, no. 8, pp. 3017–3029, 1972, https://doi.org/10.1103/PhysRevB.5.3017.

[38] D. Chandler-Horowitz and P. M. Amirtharaj, "High-accuracy, midinfrared ($450\,\mathrm{cm}^{-1} \leq \omega \leq 4000\,\mathrm{cm}^{-1}$) refractive index values of silicon", *Journal of Applied Physics*, vol. 97, no. 12, pp. 0–8, 2005, https://doi.org/10.1063/1.1923612.

[39] M. Kimata, "Trends in small-format infrared array sensors", *Proceedings of IEEE Sensors*, pp. 9–12, 2013, https://doi.org/10.1109/ICSENS.2013.6688495.

[40] R. Yamazaki, A. Obana, and M. Kimata, "Microlens for uncooled infrared array sensor", *Electronics and Communications in Japan*, vol. 96, pp. 1-8, 2013, https://doi.org/10.1002/ecj.11453.

[41] D. W. Prather, "Design and application of subwavelength diffractive lenses for integration with infrared photodetectors", *Opt. Eng.* vol. 38, p. 870, 1999, https://doi.org/10.1117/1.602256.

Received 4 June 2022

M. Yusuf Tanrikulu was born in Tarsus, Turkey, in 1978. He received the BS, MS, and PhD degrees (with high honors) in electrical and electronics engineering from Middle East Technical University (METU), Ankara, Turkey. Focused on the design and implementation of uncooled infrared microbolometer arrays using a surface micromachined MEMS technology. From 2000 to 2007 he was a Research Assistant with Department of Electrical and Electronics Eng., METU, Ankara, Turkey, and from 2008 to 2013 he was a Scientific Project Specialist in METU MEMS Center. From 2013 to 2018 he was an Assistant Professor with the Electrical-Electronics Department, Adana Alparslan Turkes Science and Technology University and since 2018 he has been and Associate Professor in the same department. His research interests include uncooled infrared detectors, microelectromechanical systems, and semiconductor material development and characterization.