Wavelength selective wideband uncooled infrared sensor using a two-dimensional plasmonic absorber

Shinpei Ogawa
Junya Komoda
Kyohei Masuda
Masafumi Kimata
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Shinpei Ogawa,a,* Junya Komoda,b Kyohei Masuda,b and Masafumi Kimata,b,*

aAdvanced Technology R&D Center, Mitsubishi Electric Corporation, 8-1-1 Tsukaguchi-Honmachi, Amagasaki, Hyogo 661-8661, Japan
bRitsumeikan University, College of Science and Engineering, 1-1-1 Noji-higashi, Kusatsu, Shiga 525-8577, Japan

Abstract. A wavelength selective wideband uncooled infrared (IR) sensor that detects middle-wavelength and long-wavelength IR (MWIR and LWIR) regions has been developed using a two-dimensional plasmonic absorber (2-D PLA). The 2-D PLA has a Au-based 2-D periodic dimple-array structure, where photons can be manipulated using a spoof surface plasmon. Numerical investigations demonstrate that the absorption wavelength can be designed according to the surface period of dimples over a wide wavelength range (MWIR and LWIR regions). A microelectromechanical system-based uncooled IR sensor with a 2-D PLA was fabricated using complementary metal oxide semiconductor and micromachining techniques. Measurement of the spectral responsivity shows that the selective enhancement of responsivity is achieved over both MWIR and LWIR regions, where the wavelength of the responsivity peak coincides with the dimple period of the 2-D PLA. The results provide direct evidence that a wideband wavelength selective IR sensor can be realized simply by design of the 2-D PLA surface structure without the need for vertical control in terms of gap or thickness.

1 Introduction

There has been increasing interest in the advanced functions of uncooled infrared (IR) image sensors with microelectromechanical system (MEMS)-based pixel structures1 to expand the applications of IR sensing.2 In particular, there is much in a spectral discrimination function that enables uncooled IR sensors to identify objects through their radiation spectrum, which is useful for many applications such as fire detection and gas analysis. A pixel array in which each pixel has a different absorption wavelength could be used to realize multicolor imaging at IR wavelengths, which would provide the same benefits as the RGB pixels of image sensors in the visible region. Therefore, wavelength selectivity is a promising function for an advanced IR sensing.3 Many approaches have been proposed to achieve this, such as band-pass filters,4 optical resonant structures,5,6 and multilayer structures.7,8,9 However, the attachment of external optical systems requires additional space and increases the cost. The optical resonant structures and multilayer structures require gap or thickness control of the dielectric layer to achieve maximum absorption according to the wavelength.10,11 Therefore, such typical approaches have difficulty in integrating different pixels in an array for a multicolor imaging.

We have applied plasmonics to address this challenge. A great deal of interest has developed in plasmonics,12–14 which is a type of uncooled IR sensor. The 2-D PLA has a 2-D periodic array of round dimples on the surface, where photons can be manipulated by spoof surface plasmon polaritons (SPPs).22 Such an asymmetric structure as a one-dimensional grating produces a strong polarization dependency, which is disadvantageous for the IR image sensors. Therefore, a 2-D surface structure with a square lattice and a round dimple was adopted, where only the thin surface metal layer absorbs the incident light.

We have previously reported the absorption properties of a PLA in the MWIR region,23 where the absorption wavelength was almost the same as the period of the 2-D PLA, due to the spoof SPP mode. The basic design of the Au-based 2-D PLA as an IR absorber for the LWIR at normal incidence was achieved using the rigorous coupled wavelength analysis method. Figure 1(b) shows the wavelength...
absorption of the Au-based 2-D PLA as a function of the period from 8.0 to 12.0 μm with a fixed dimple diameter of 6.0 μm and a depth of 1.5 μm. The strong wavelength selective absorption is evident over the LWIR region, as for the MWIR region, and this can be controlled according to the surface period. This satisfies the requirements for an uncooled wideband IR sensor with the wavelength selective function. Figure 1(c) shows the concept of the pixel array with various 2-D PLAs for multispectral imaging.

3 Sensor Fabrication

A MEMS-based uncooled IR sensor with 2-D PLAs was developed. The 2-D PLAs are fabricated by forming a Au layer on perforated SiO$_2$. However, the back side of the SiO$_2$ layer absorbs scattered light in the LWIR region. To address this issue, an Al layer is introduced to the back side of the 2-D PLA to reflect scattered light. Figure 2 shows the process used to fabricate the MEMS-based thermopile with 2-D PLA: (a) The devices are fabricated on 6-in p-type Si(1 0 0) substrates using a standard complementary metal oxide semiconductor (CMOS) process. Etching holes are formed by reactive-ion etching (RIE). A 1.5-μm thick SiO$_2$ layer is formed on the absorber area. (b) The periodic structure is formed on SiO$_2$ using a dry etching process. (c) Cr/Au layers are sputtered on the perforated SiO$_2$. (d) The thermally isolated freestanding structure is completed by bulk-micromachining.
sputtering. Scanning electron microscopy (SEM) observation confirmed that the Cr/Au layers were uniformly coated on both the bottom and side walls of the etched holes to complete the concave Au structure. (d) The wafers are diced into chips. The Si is anisotropically etched using tetramethylammonium hydroxide through the etching holes to form the cavity under the IR absorber area. Finally, a thermally isolated freestanding structure is completed on which the 2-D PLA is formed.

Figure 3(a) shows an SEM image of the developed thermopile. The detector area, which is 300 \( \times \) 200 \( \mu \text{m}^2 \), is surrounded by the long thermal isolation legs to reduce the thermal conductance. Various sensors with different 2-D PLA structures were fabricated on the same wafer. The respective diameters and periods of the surface structures were as follows: (i) 3.0 and 4.0 \( \mu \text{m} \), (ii) 3.0 and 4.5 \( \mu \text{m} \), (iii) 4.0 and 5.0 \( \mu \text{m} \), (iv) 4.0 and 6.5 \( \mu \text{m} \), (v) 6.0 and 7.0 \( \mu \text{m} \), (vi) 6.0 and 8.0 \( \mu \text{m} \), (vii) 6.0 and 9.0 \( \mu \text{m} \), and (viii) 6.0 and 10.5 \( \mu \text{m} \). The depth was fixed at 1.5 \( \mu \text{m} \) for all sensors.

Figures 3(b) and 3(c) show representative magnified SEM images of two 2-D PLA surfaces. Two periodic structures of 2-D PLA were formed, denoted sensors (ii) and (vii) for MWIR and LWIR, respectively. The diameters and periods of the surface structures of sensor (vii) are linearly twice those of sensor (ii). The depth was fixed at 1.5 \( \mu \text{m} \) for both sensors. Figure 3(d) shows a schematic of the 2-D PLA structure with the Al reflection layer.

### 4 Measurements

The wavelength selective properties of the 2-D PLA were investigated. The sensors were set in a vacuum chamber with a Ge window under a pressure of 1 Pa to prevent thermal conduction loss through the atmosphere. The sample was irradiated with IR rays from a blackbody through narrow band-pass filters for the selection of the evaluation wavelengths. The typical full width at half maximum was 80 nm. A pinhole was used to restrict the incident light to the 2-D PLA region only. The output voltage was measured and the responsivity was calculated as the ratio between the output voltage difference of the on and off states and the input power. The input power was calculated according to the measurement system parameters, absorber area, transmittance from the blackbody to the sensor through the atmosphere, narrow band-pass filters and the Ge window, and the spectral radiant emittance equation at the evaluated wavelength as previously reported.

The responsivities of sensors (ii) and (vii) were measured first. Figure 4 shows the normalized responsivity of both sensors with clear responsivity peaks in the MWIR and LWIR regions, which coincides with the period of each sensor. The surface structural parameter of sensor (vii) is linearly twice that of sensor (ii) and each sensor has almost the same responsivity. The responsivities of various other sensors were also measured and the results are shown in Fig. 5. The wavelength selectivity was realized for all sensors over a wide range of MWIR and LWIR. The each peak wavelength of responsivity coincides with the periods of each 2-D PLA and these are plotted in Fig. 6 as a function of the surface period of 2-D PLA. These results clearly demonstrate that the detection wavelength is proportional to the surface period; therefore the theory and experimental results are in good agreement.

These results demonstrate that strong absorption occurs due to the spoof SPPs, where responsivity is selectively enhanced and the detection wavelength can be controlled according to the surface period of the 2-D PLA for both MWIR and LWIR regions.
5 Conclusions

An MEMS-based uncooled IR sensor with 2-D PLAs was fabricated using standard CMOS and micromachining techniques. Responsivity measurements demonstrate that the selective enhancement of the responsivity was achieved over both MWIR and LWIR regions, which is coincident with the period of the 2-D PLA. The obtained responsivities are consistent with the calculated absorption results. These results are direct evidence that the wavelength selective wideband uncooled IR sensor can be realized simply by the design of the 2-D PLA surface structure without the need for filters or multilayer structures. Control of the detection wavelength according to the 2-D PLA can be applied to other types of thermal IR sensors, such as bolometers and silicon-on-insulator diodes.\textsuperscript{25,26} The results presented here should be a significant contribution to the development of novel multicolor imaging for IR sensors.

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References

1. Y. Gianchandani, O. Tabata, and H. Zappe, Comprehensive Microsystems, Vol. 3, pp. 113–163, Elsevier, Amsterdam (2008).
2. M. Vollmer and K.-P. Mollmann, Infrared Thermal Imaging: Fundamentals, Research and Applications, Wiley-VHC, Weinheim (2010).
3. J. J. Talghader, A. S. Gawarikar, and R. P. Shea, “Spectral selectivity in infrared thermal detection,” Light Sci. Appl. 1, e24 (2012).
4. R. Haidar et al., “Free-standing subwavelength metallic gratings for snapshot multispectral imaging,” Appl. Phys. Lett. 96(22), 221104 (2010).
5. S. W. Han et al., “Design of infrared wavelength-selective microbolometers using planar multimode detectors,” Electron. Lett. 40(22), 1410–1411 (2004).
6. Y. Wang, B. J. Potter, and J. J. Talghader, “Coupled absorption filters for thermal detectors,” Opt. Lett. 31(13), 1945–1947 (2006).
7. M. Diem, T. Koschny, and C. M. Soukoulis, “Wide-angle perfect absorber/thermal emitter in the terahertz regime,” Phys. Rev. B 79(3), 033101 (2009).
8. T. Maier and H. Brückl, “Wavelength-tunable microbolometers with metamaterial absorbers,” Opt. Lett. 34(19), 3012–3014 (2009).
9. X. Liu et al., “Infrared spatial and frequency selective metamaterial with near-unity absorbance,” Phys. Rev. Lett. 104(20), 207403 (2010).
10. T. Maier and H. Brückl, “Multispectral microbolometers for the midinfrared,” Opt. Lett. 35(22), 3766–3768 (2010).
11. J. Hao et al., “High performance optical absorber based on a plasmonic metamaterial,” Appl. Phys. Lett. 96(25), 251104 (2010).
12. W. L. Barnes, A. Dereux, and T. W. Ebbesen, “Surface plasmon subwavelength optics,” Nature 424(6950), 824–830 (2003).
13. D. K. Gramotnev and S. I. Bozhevolnyi, “Plasmonics beyond the diffraction limit,” Nat. Photonics 4(1), 83–91 (2010).
14. S. Kawata, “Plasmonics: Future Outlook,” Jpn. J. Appl. Phys. 52(1), 010001 (2013).
15. E. Yablonovitch, “Inhibited spontaneous emission in solid-state physics and electronics,” Phys. Rev. Lett. 58(20), 2059–2062 (1987).
16. S. Ogawa et al., “Control of light emission by 3D photonic crystals,” Science 305(5681), 227–229 (2004).
17. Y. Ohhita and H. Yamada, “Photonic crystals for the application to spectrometers and wavelength filters,” IEICE Electron. Express 10(8), 20132001 (2013).
18. T. W. Ebbesen et al., “Extraordinary optical transmission through sub-wavelength hole arrays,” Nature 391(6668), 667–669 (1998).
19. J. B. Pendry, L. Martin-Moreno, and F. J. Garcia-Vidal, “Mimicking surface plasmons with structured surfaces,” Science 305(5685), 847–848 (2004).
20. W. Barnes and R. Sambles, “Only skin deep,” Science 305(5685), 785–786 (2004).
21. F. J. Garcia-Vidal, L. Martin-Moreno, and J. B. Pendry, “Surfaces with holes in them: new plasmonic metamaterials,” J. Opt. A 7(2), S97–S101 (2005).
22. R. Stanley, “Plasmonics in the mid-infrared,” Nat. Photonics 6(7), 409–411 (2012).
Shinpei Ogawa received his BE, ME, and PhD degrees from the Department of Electronic Science and Engineering, Kyoto University, Japan, in 2000, 2002, and 2005, respectively. He has been with the Advanced Technology R&D Center, Mitsubishi Electric Corporation, Amagasaki, Japan, since 2005. He works on the development of various MEMS devices, including RF-MEMS switches, TSV, optical sensors, infrared sensors, and packaging technology. His current research interests are photonic and plasmonic devices integrated with MEMS technology.

Junya Komoda received his BE and ME degrees from the College of Science and Engineering, Ritsumeikan University, Japan, in 2011 and 2013, respectively.

Kyohei Masuda received his BE degree from the College of Science and Engineering, Ritsumeikan University, Japan, in 2012. He is currently working for his ME degree in the College of Science and Engineering, Ritsumeikan University.

Masafumi Kimata received his MS degrees from Nagoya University in 1976, and received his PhD degree from Osaka University in 1992. He joined Mitsubishi Electric Corporation in 1976, and retired from Mitsubishi Electric in 2004. Currently, he is a professor of Ritsumeikai University, where he continues his research on MEMS-based uncooled infrared focal plane arrays and type-II superlattice infrared focal plane arrays. He is a fellow of SPIE.

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