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Silicon-coated gold nanodiffraction grating structures as plasmonic absorbers for shortwavelength infrared light

Tsubota, Tatsuya ; Arai, Naoyuki ; Harada, Atsuya ; Uesugi, Akio ; Sugano, Koji ; Isono, Yoshitada

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Silicon-coated gold nano diffraction grating 1

structures as plasmonic absorber for short 2

wavelength infrared light 3

TATSUYA TSUBOTA,¹ NAOYUKI ARAI,¹ ATSUYA HARADA,¹ AKIO UESUGI,¹ 4

5 KOJI SUGANO,^{1,*} AND YOSHITADA ISONO^{1,}

6 7 8 ¹Department of Mechanical Engineering, Graduate School of Engineering, Kobe University, Kobe, Hyogo 657-8501, Japan

*sugano@mech.kobe-u.ac.jp

9 Abstract: As a plasmonic absorber for short-wavelength infrared hyperspectral imaging, a 10 silicon-coated gold nano diffraction grating structure is proposed. This plasmonic absorber 11 leads to absorption peaks in short-wavelength infrared region by high refractive index of silicon 12 coating on gold grating. It is relatively easy to be fabricated with smaller size than those of 13 already known absorbers. By performing fabrication, simulation, and measurement, we 14 demonstrate the sharp absorption peaks of short-wavelength infrared light using only 400-1000 15 nm grating interval. We believe this miniaturized absorber will enable to be applied to 16 hyperspectral imaging without a spectroscope owing to its sharp absorption peak at a specific 17 wavelength.

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19 1. Introduction

20 In recent years, demand for non-destructive and non-contact inspections using short-21 wavelength infrared (SWIR, wavelength range: 1-3 µm) spectroscopy has increased. SWIR 22 light is highly transparent to substances such as package films and liquids, as well as unique 23 absorption characteristics to water. Water absorbs only specific wavelength light (1450-1500 24 nm) in contrast to other wavelengths. Therefore, changes in the amount of water generated due 25 to spoilage inside food can be detected easily. SWIR spectroscopy is used in various 26 applications, such as medicine inspections [1], medical diagnoses [2, 3], and food inspections 27 [4-7]. However, the currently marketed SWIR detectors require optical equipment such as a 28 diffraction grating spectroscope for hyperspectral imaging [8, 9]. The additional equipment 29 results in high cost and large device size, as well as considerable detection noise due to radiant 30 heat from optical components [10]. Therefore, absorbers with wavelength dependence in the 31 SWIR wavelength range of detectors are expected to enable hyperspectral imaging without 32 requiring diffraction grating spectroscopy. By integrating the structures of SWIR detectors and 33 absorbers with various absorption peak wavelengths as one imaging pixel, various wavelength 34 bands can be detected instantly without using the conventional diffraction grating spectroscope. 35 Various studies regarding wavelength-dependent plasmonic absorbers have been reported [11, 36 12], where metal nanostructures such as nanorods [13, 14], nanofins [15-17], metal-insulator-37 metal (MIM) [18] and grating structures [19-21] for bio-chemical or microelectromechanical system (MEMS) optical sensors [21-25] have been reported. However, a full width at half 38 39 maximum (FWHM) of the structures proposed in Ref. [14] is about 170 nm. Therefore, it is 40 challenging to obtain a narrow-band absorption peak using nanorods. Nanofins are challenging 41 to fabricate because of their high-aspect-ratio nanostructures, which result in low structural 42 controllability. Because MIM structures control the absorption wavelength based on the 43 thickness of the insulator thin film, it is difficult to fabricate multiple absorbers with different 44 film thicknesses on a same substrate to yield different absorption peak wavelengths for sensor 45 applications. Grating structures have been used as spectroscopic elements because they can

46 yield a narrow band absorption peak and good controllability for absorption peak wavelengths 47 by changing the grating interval. The interval required for SWIR absorption is similar to the 48 wavelength, as described in Section 2. Thus, absorber miniaturization for high-spatial-49 resolution hyperspectral imaging is restricted. Hence, we focus on miniaturized SWIR 49 absorbers with a narrow band absorption peak with a FWHM of less than 100 nm in the 49 wavelength ranged from 1000 to 2000 nm (generally used for food inspection), excellent 50 controllability, and a wide control wavelength range on the same substrate.

Herein, we propose silicon (Si)-coated gold (Au) nano diffraction grating structures, which are relatively easy to fabricate because of the excellent compatibility of these materials in nano/microscale MEMS fabrication. The optical characteristics of grating structures are significantly affected by a refractive index (dielectric index) of the surroundings. Therefore, by coating the grating structures with Si, it is expected to reduce the grating interval, thereby resulting in a high refractive index and an excellent integration with MEMS.

59 In this study, we fabricated, simulated, and measured Si-coated Au nano diffraction grating 60 structures. The effects of the Si coating thickness and the height, grating interval, and width of 61 the Au nano diffraction grating structures on the optical characteristics are reported herein.

62 2. Principle of NIR absorption

63 Propagating electromagnetic waves combine with the collective vibration of free electrons at 64 the interface between a metal and dielectric under certain conditions in the resonance state [26-65 29]. This phenomenon is known as surface plasmon polariton (SPP), and its behavior can be 66 derived from Maxwell's equations. In this phenomenon, surface plasmon wave (SPW) 67 propagates along the interface between the dielectric and metal. The SPW wavenumber (k_{sp}) 68 is expressed as follows:

$$k_{sp} = \pm \frac{2\pi}{\lambda} Re\left(\sqrt{\frac{\varepsilon_s \varepsilon_m}{\varepsilon_s + \varepsilon_m}}\right),\tag{1}$$

69 where λ , ε_s , and ε_m denote the wavelength of light in vacuum, permittivity of dielectric, and 70 complex permittivity of the metal, respectively.

71 The horizontal component of the diffracted light at an incidence angle $\theta(k_x)$ is expressed 72 as follows:

$$k_x = \frac{2\pi}{\lambda} \sqrt{\varepsilon_s} \sin \theta + \frac{2m\pi}{d},\tag{2}$$

73 where *m* and *d* denote the diffraction mode with a positive or negative integer and a grating 74 interval, respectively. SPP is generated when k_{sp} and k_x match, and SPP can be observed at 75 the wavelength intersecting k_{sp} and k_x . To satisfy the resonance condition, a metal whose real 76 part of the refractive index is negative must be used. Gold, silver, and aluminum are typically 77 used in wavelength regions of visible light and longer [30]. We used Au because it is highly 78 compatible with MEMS and less likely to cause surface oxidation.

79 When we consider a simple case in which light is incident on an Au plane, k_x contains no 80 second term. Consequently, no intersections exist and hence no SPP generation. Although a 81 method using a prism as a medium is easy and often used to match k_{sp} and k_{x} , it prevents the 82 miniaturization of sensors. Therefore, absorbers with metal diffraction grating structures were 83 used in this study. The resonance wavenumber (or wavelength) and the electromagnetic 84 intensity are affected by d and θ . As an example, their relationships when using Au diffraction 85 gratings with d = 600 nm and d = 2000 nm are shown in Figs. 1(a) and (b), respectively. x 86 and y axes mean the wavenumber and the wavelength of k_{sp} and k_x , respectively. In this study, 87 the target wavelength ranged from 1000 to 2000 nm. The angle of incidence was fixed at $\theta =$ 88 30° because of the specifications of the measuring equipment used in this study, as described 89 in Section 3. In the case of d = 600 nm, as shown in Fig. 1(a), no intersections were observed 90 in the target wavelength range. By contrast, in the case of d = 2000 nm, as shown in Fig. 1(b), 91 intersections were observed at wavelengths of 1506, 1021, and 1007 nm. Therefore, by 92 selecting the appropriate d and θ , SPP is generated by simply injecting light without an 93 additional optical system, such as a prism, because of the intersection. In this regard, several 94 studies pertaining to the control of the absorption wavelength by changing d or θ have been 95 reported [31, 32].

96 However, because a sufficient number of diffraction gratings is required to generate SPPs, 97 it is difficult to reduce the size of an absorber with d = 2000 nm. Therefore, we propose Si-98 coated Au nano diffraction grating structures. The relationship between k_{sp} and k_x at d = 60099 nm is shown in Fig. 1(c). We can confirm that intersection wavelengths of 1628, 1263, and 100 1146 nm were observed; in other words, SPP is generated in the SWIR region. In the cases 101 shown in Figs. 1(a) and (b), the SPW propagates at the interface between vacuum (or 102 atmosphere) and Au. By coating Si (which has a dielectric constant of 11.8-12.8 and a 103 refractive index of 3.44–3.58 in the SWIR region) on the Au diffraction gratings, the SPW 104 propagates between Au and Si, and the absorption wavelength can be controlled. Therefore, we 105 assume that SPPs can be generated in the SWIR region even at a smaller grating interval of 106 approximately 30% or less owing to the refractive index of Si. This is expected to contribute to 107 the further miniaturization of SWIR sensors. 108



Fig. 1. Calculated relationship between resonance wavelength and wavenumber of SPW wavenumber k_{sp} and horizontal component of diffracted light k_x at wavelength ranging from 1000 to 2000 nm. x and y axis mean the wavenumber and the wavelength of k_{sp} and k_x , respectively. Angle of incidence fixed at $\theta = 30^{\circ}$. Relationship when using Au diffraction gratings with (a) d = 600 nm, (b) d = 2000 nm (both without Si coating), and (c) d = 600 nm (with Si coating).

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117 3. Methods

118 3.1 Structure

Figure 2 shows a schematic image and parameters of the Si-coated Au nano diffraction grating structures. The cross-sectional structures of the Au gratings and the coated Si depend on the fabrication process. We carried out the preliminary fabrication experiments to obtain the resulting structure and the available structural dimensions. In Section 3.1, the fabrication process, the fabrication result, and the parameters for simulations and experiments were presented.

For the diffraction grating structures, line and space patterns with length of 20 μm were fabricated on a Au thin film. First, a 10-nm-thick Cr thin film and a 100-nm-thick Au thin film were sequentially deposited on a bulk Si wafer using electron beam (EB) vapor deposition equipment. Next, diluted positive resist ZEP 520A (Nippon Zeon) was spin coated onto the Au

129 layer for EB lithography, followed by pre-baking on a hot plate. Subsequently, EB lithography

130 of the Au nano diffraction grating patterns was performed. Subsequently, Au vacuum

deposition and subsequent lift-off were performed to fabricate the Au nano diffraction gratings.

- 132 Finally, Si was deposited via sputtering.
- 133





Fig. 2. Schematic illustration and parameters of Si-coated Au nano diffraction grating structures. Au line and space patterns with 20 μ m length are fabricated on Au thin film and then Si is deposited.

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139 Figure 3 shows scanning electron microscopy (SEM) images of the fabricated Si-coated Au 140 nano diffraction grating structures. Figures 3(a) and (b) show the Au nano diffraction gratings 141 before they were coated with Si. Figures 3(c) and (d) show the cross-sectional images. The 142 cross-sectional shape of the nano diffraction gratings was trapezoidal. The coating Si was 143 complicated structure that covered the nano diffraction gratings and contained dents. The 144 measured average values of the Si coating thickness (t), grating height (h), grating interval (d), 145 and grating width (W) of the Si-coated Au nano diffraction grating structures are shown in 146 Table 1. t was controlled by sputtering time for absorption peaks in the SWIR region. These 147 were determined as a parameter for simulations and experiments. 148



Fig. 3. SEM images of fabricated Si-coated Au nano diffraction grating structures, which are fabricated on Au thin film via EB lithography, Au vapor deposition, and Si sputtering. (a), (b) show top view of Au nano diffraction gratings prior to coating Si. (c), (d) show cross-sectional images of Au nano diffraction gratings after coating Si.

155Table 1. Average values of measured grating height (h), thickness of Si coating (t), grating interval (d), and156grating width (W) of Au nano diffraction grating structures

Dimension parameters	Design [nm]
Grating height (h)	40
Si coating thickness (t) (Sputtering time [min])	0, 77, 93, 102, 119 (0, 12.5, 15.0, 17.5, 20.0)
Grating interval (d)	400, 500, 600, 700, 800, 900, 1000
Grating width (W)	23, 45, 69, 101, 121, 141, 170, 202

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158 3.2 Modeling

159 As a finite differential time domain (FDTD) method, we used FDTD Solutions (Lumerical), 160 which is commercially available simulation software. The simulation model shown in Fig. 4 161 was designed based on the dimensions and shapes obtained from the SEM images. In 162 measurement, angle of light θ through the reflective objective lens irradiating the absorber 163 ranged from 16° to 45°. Therefore, we set $\theta = 30^\circ$ because the median value had peak intensity. 164 We applied the broadband fixed angle source technique (BFAST) to the light source, which is 165 a plane wave and can calibrate different incident angles for each wavelength. The BFAST is 166 effective when using an angled light source in a periodic structure. For the periodic boundary 167 condition, we used the BFAST symmetric boundary condition to shorten the simulation time 168 for the x- and y-planes. The perfectly matched layer absorption boundary condition was used 169 for the z -plane. The width of the simulation area in the x-direction varied from 400 to 1000 170 nm, which corresponded to d. The length and height of the simulation area were set to 50 and 171 5400 nm, respectively, in the y- and z-directions. The data by Palik was used to set the complex 172 refractive index of Au and Si as shown in Figs. 4(c)-(f). The mesh size of the complicated 173 structures such as a dent or a corner was set to 3 nm. The mesh size was determined because 174 no significant effect was confirmed at 3 nm or less. The auto-meshing function of the FDTD 175 software was adapted to the other part. In the simulation, the absorption spectra of the Si-coated 176 Au nano-diffraction grating structures were calculated. We investigated the effects of h, t, d, 177 and W on the absorption spectrum and absorption peak wavelengths. The reflection and 178 transmission spectra were calculated via FDTD simulation at wavelength of 1000-2000 nm, 179 and the absorption was calculated as A = 100 - T - R. In addition, the electric field intensity 180 distributions at the absorption peak wavelengths were evaluated. 181



189 3.3 Measurement

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190 Absorption A [%] is expressed in terms of transmittance T [%] and reflectance R [%] as follows: 191 A = 100 - T - R. In this study, the absorption spectra were calculated as A = 100 - R because 192 the transmission of the Au thin film was negligible since the thickness of the Au layer was 100 193 nm, which provided a low transmittance of 2% or less calculated by the simulation. The 194 reflectance was measured using an ultraviolet-visible/near-infrared microspectrophotometer 195 (MSV-5200DGK, JASCO). A Cassegrain-type reflective objective lens equipped with a 196 microspectrophotometer was used. A plane Au sample without patterns was used as a reference 197 for the reflection spectra. The wavelength range for measurement was set from 1000 to 2000 198 nm. 199

200 4. Results

201 4.1 Effects of Si coating and grating height (h)

202 We investigated the effects of the grating height and Si coating using the FDTD simulation. 203 Figure 5 shows the simulated absorption spectra at t = 102 nm, d = 600 nm, W = 101 nm, 204 and h = 30-50 nm. At h = 30 nm, we observed four absorption peaks at wavelengths of 1674, 205 1452, 1242, and 1170 nm, although no absorption peaks were observed without Si coating, as 206 shown in Fig. 5(i). The spectrum without a Si coating (t = 0 nm) shows the absorption of less 207 than 4% without peaks. We found the Si coating contributed to the absorption of the SWIR 208 light in simulation as mentioned in Sections 1 and 2. The above mentioned absorption peaks 209 are referred to herein as the first, second, third, and fourth peaks, respectively. They are the 210 ordinal numbers from longer wavelengths, and don't correspond to the diffraction mode shown in Eq. (2) and Fig. 1. We discovered the absorption depended significantly on h. In particular, no second peak was observed when h = 40-50 nm.

213 Figure 6 shows the electric field intensity distributions of each simulated absorption peak 214 wavelength for h = 30 nm. As shown in Figs. 6(c) and (d), the electric field at the corners of 215 the trapezoidal upper base of the Au nano diffraction gratings are enhanced, and the 216 electromagnetic waves propagate at the interface between Au and Si at wavelengths of 1242 217 nm (third) and 1170 nm (fourth). As shown in Figs. 6(a) and (b), the electric field strengthened 218 in the dented part of the Si-coated gratings at wavelengths of 1674 nm (first) and 1452 nm 219 (second). The first and second peaks indicated more significant effects by the dented part on 220 the peak height than the third and fourth peaks. The lower absorption peaks were assumed to 221 be due to the greater distance from the Au/Si interface to the dented part than to the Au corners, 222 which resulted in a lower electric field (Fig. 6) and a greater absorption height. The dented part 223 included significantly complicated structures, particularly in a narrow space.

224 Figure 7 shows the simulated and the experimentally measured absorption spectra of the 225 absorbers with d = 600 nm, W = 101 nm, and t = 102 nm or t = 0 nm (without a Si coating). 226 When t = 0 nm, an absorption of 5% or less without peaks at wavelengths from 1000 to 2000 227 nm was observed, whereas the absorber with a Si coating of t = 102 nm indicated large 228 absorption peaks at wavelengths of 1591, 1412, 1165, and 1100 nm. We also confirmed the Si 229 coating contributed to the absorption of the SWIR light in experiment. When t = 0 nm, neither 230 the simulated nor measured results indicated an absorption peak in the SWIR region. These 231 results are consistent with theory because the case does not involve any intersections in the 232 dispersion relation shown in Fig. 1(a). The second peak has a high absorption rate of 84.8% 233 and a narrow bandwidth with a FWHM of 78 nm in the SWIR region. This is well below about 234 100 nm of the absorbers reported in recent study [19].

235 In this paragraph, the simulated and the experimental results were compared. No second 236 peak was observed when h = 40-50 nm, and the absorption (peak heights) of the simulated 237 results for the first and second peaks were greatly different from those of the experimental 238 results. The experimentally measured absorption at the wavelength of 1412 nm (second) was 239 84.8%, whereas that of 1452 nm (second) was 12.5% in the simulation for h = 30 nm, which 240 was significantly less than the measured value. Owing to the complicated structures such as 241 dented part with narrow space, the accurate modeling for simulation is difficult; hence, the 242 experimental and simulated results for the absorption height differ. In addition, we considered 243 the complex refractive index of the sputtered Si differs from the Palik data used in this study 244 because the sputtered Si is thought to be amorphous [33]. However, the simulated results 245 exhibited the tendency of the experimental results for the peak wavelengths. The diffraction 246 gratings with h = 30 nm indicated four absorption peaks in simulation as well as the 247 experimental results. We confirmed that the absorption peak wavelengths of the simulated 248 results were similar to those of the experimental results, where it shifted to longer wavelength. 249 Hence, we used a model with h = 30 nm in the subsequent simulation to clarify the absorption 250 peaks.

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Fig. 7. Experimentally-measured (Exp.) and simulated (Sim.) absorption spectra of Si-coated Au nano diffraction grating absorbers for d = 600 nm, W = 101 nm, and t = 102 nm at wavelength ranging from 1000 to 2000 nm. Case of t = 0 nm (without a Si coating) is shown.

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270 4.2 Effect of Si coating thickness (t)

271 Next, we investigated the effect of the Si coating thickness (t). Figures 8(a) and (b) show the 272 simulated and experimentally-measured absorption spectra at t = 0, 77, 93, 102, and 119 nm; 273 d = 600 nm; and W = 101 nm, respectively. The absorption spectra for the case without Au 274 nano diffraction gratings are also shown.

275 In simulation, it was confirmed that the absorbers without grating structures indicated a 276 slight change in the absorption wavelength depending on the Si coating thickness as shown in 277 Fig. 8 (dotted lines); however, a clear absorption peak was not observed. On the other hands, 278 the absorbers with grating structures showed clear absorption peaks. We confirmed the 279 absorption peaks in SWIR region of 1000-2000 nm at t ranging from 77 to 119 nm used in this 280 study. We found the absorption peak wavelengths shifted to longer as t increased focusing on 281 the first and second peaks because these peaks were clearly observed without peak's 282 superposition. The dependency of Si coating thickness is observed because the electric field of 283 SPW goes out of the Si thin layer, ranging from 77 to 119 nm, as shown in Fig. 6.

284 In measurement, when t = 77 nm, peak wavelengths were observed at 1387 nm (first), 285 1239 nm (second), 1081 nm (third), and 1009 nm (fourth). The peak wavelengths at t = 77 nm 286 were shorter than those at t = 93 nm. When t = 119 nm, the absorption peaks appeared at 287 1694 nm (first), 1493 nm (second), 1196 nm (third), and 1123 nm (fourth). We found the four 288 absorption peak wavelengths shifted to longer with increasing t as with the simulation. The 289 wavelength of the second peak increased by 254 nm from 1239 to 1493 nm as t increased from 290 77 to 119 nm. The peak wavelengths can be controlled by changing t. The relationship between 291 t and the absorption peak wavelengths is shown in Fig. 9. In both results, we confirmed the 292 absorption peaks due to the Si coating, and the absorption peak wavelengths shifted to longer 293 as t increased.



Fig. 8. Effect of Si coating thickness (t). (a) Simulated and (b) experimentally- measured spectra of Si-coated Au nano diffraction grating absorbers for t = (i) 77, (ii) 93, (iii) 102, (iv) 119, (v) 0 nm; d = 600 nm; and W = 101 nm at wavelength ranging from 1000 to 2000 nm. Solid and dotted lines indicate spectra in cases with and without Au nano diffraction gratings, respectively. Absorption ranges of these spectral graph in simulation and experiment are set from 0 to 50% and from 0 to 100%, respectively.



Fig. 9. Relationship between t and absorption peak wavelength ranging from 1000 to 2000 nm based on simulated and experimentally-measured results.

308 4.3 Effect of grating interval (d)

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Next, we investigated the effect of the grating interval (d). Figures 10(a) and (b) show the simulated and experimentally-measured absorption spectra at t = 102 nm, d = 400-1000 nm, and W = 101 nm, respectively. The absorption spectrum for the case without Au nano diffraction gratings are also shown in (viii).

In simulation, we found the absorption peak wavelengths shifted to longer as d increased focusing on the first and second peaks. This tendency is consistent with the theory as mentioned in Section 2. With increasing d from 400 to 1000 nm, the first and second peaks were shifted from 1463 to 1961 nm, and from 1238 to 1679 nm, respectively.

317 In measurement, when d = 400 nm, the peak wavelengths appeared at 1370 nm (first), 318 1189 nm (second), and 1025 nm (third). Fourth and higher wavelength peaks were not 319 observed. The fourth and fifth peaks with small absorption appeared at d = 600 and 700 nm, 320 respectively, when d increased. The peak wavelengths increased with d. When d = 1000 nm, the spectrum indicated absorption peaks at 1891 nm (first), 1693 nm (second), 1479 nm (third), and 1356 nm (fourth). At wavelengths shorter than the fourth peak, small absorption peaks appeared. The absorption peak wavelengths shifted to longer from 1189 to 1693 nm as dincreased from 400 to 1000 nm, as indicated by the second peak, which demonstrated the highest absorption. The relationship between d and absorption peak wavelengths in simulation and experiment is shown in Fig. 11. From both results, we confirmed the absorption peak wavelengths shifted to longer as d increased, indicating good agreement between both results.





Fig. 10. Effect of grating interval (d). (a) Simulated and (b) experimentally-measured absorption spectra of Si-coated Au nano diffraction grating absorbers for t = 102 nm, d = 400-1000 nm ((i)-(vii)), and W = 101 nm at wavelengths ranging from 1000 to 2000 nm. Case without Au nano diffraction gratings is shown (viii). Absorption ranges of these spectral graph in simulation and experiment are set from 0 to 50% and from 0 to 100%, respectively.





Fig. 11. Relationship between d and absorption peak wavelength ranging from 1000 to 2000 nm based on simulated and experimentally-measured results.

343 4.4 Effect of width of nano diffraction gratings (W)

344 Finally, we investigated the effect of the width of the nano diffraction gratings (W). Figures 345 12(a) and (b) show the simulated and experimentally-measured absorption spectra at t = 102346 nm, d = 600 nm, and W = 23-202 nm, respectively. In simulation, the wavelengths of the first 347 and second peaks were independent of W ranging from 23 to 202 nm. This is because the width 348 does not affect the peak wavelengths, according to the theory. In measurement, when W = 45349 nm, peak wavelengths were observed at 1610 nm (first), 1432 nm (second), 1200 nm (third), 350 and 1060 nm (fourth). When W = 170 nm, absorption peaks were observed at 1559 nm (first), 351 1438 nm (second), 1214 nm (third), and 1058 nm (fourth). The second peak wavelengths shifted 352 slightly to longer wavelengths, and the first peak shifted to shorter wavelengths as W increased. 353 The relationship between W and the absorption peak wavelengths in simulation and experiment 354 355 is shown in Fig. 13. The tendency of experiment are consistent with the simulation.



Fig. 12. Effect of width of nano diffraction gratings (W). (a) Simulated and (b) experimentallymeasured absorption spectra of Si-coated Au nano diffraction grating absorbers with effect of W for t = 102 nm, d = 600 nm, and W = 23-202 nm ((i)–(viii)) at wavelengths ranging from 1000 to 2000 nm. Case without Au nano diffraction gratings is shown in (ix). Absorption ranges of these spectral graph are set from 0 to 100% and from 0 to 50%, respectively.

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Fig. 13. Relationship between W and absorption peak wavelength ranging from 1000 to 2000 nm based on simulated and experimentally-measured results.

366 367 368 369 We discovered the effect of t or d prominent although that of W was less. By comparing 370 between the simulated and experimentally-measured results, we confirmed that both indicated 371 absorption peak wavelength shifts and hence validated the proposed structure. Furthermore, we 372 demonstrated that coating the Au diffraction grating structures with Si reduced the grating 373 interval. The grating interval of this proposed absorbers is 400-1000 nm for SWIR, which is 374 much smaller than 1050-1350 nm of the absorbers reported in recent studies [19]. Therefore, 375 we conclude that adopting the proposed absorber will result in the miniaturization of plasmonic 376 optical sensors.

377 5. Conclusion

378 We herein propose Si-coated Au nano diffraction grating structures as miniaturized SWIR 379 absorbers with a narrow band absorption peak, excellent controllability, and a wide control 380 wavelength range on a same substrate. We performed nanofabrication, simulation using the 381 FDTD method, and measurement for Si-coated Au nano diffraction grating structures. It was 382 confirmed that Si coating contributed to the absorption of SWIR light at wavelength ranging 383 from 1000 to 2000 nm owing to the high refractive index of Si. Three or four narrowband 384 absorption peaks with a FWHM of approximately 75 nm were observed, and their maximum 385 absorption was 86.6%. We found the absorption peak wavelengths shifted to longer as the Si 386 coating thickness increased. Whereas the absorption peak wavelengths shifted to longer as the 387 grating interval increased, a slight shift occurred owing to the grating width. We discovered 388 that the grating interval and Si coating thickness effectively controlled the absorption peak 389 wavelengths. Additionally, the required grating interval is 400-1000 nm, which is much smaller 390 than those of the structures reported in recent studies. The experimental results exhibited the 391 same tendency as the FDTD simulated results regarding the peak wavelengths. Therefore, we 392 believe that this absorber will enable low-cost and miniaturized optical sensors leading to non-393 destructive and non-contact inspections without requiring a spectroscope.

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401 Data availability. Data underlying the results presented in this paper are not publicly available at this time but may 402 403 be obtained from the authors upon reasonable request.

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