Transmission through randomly arranged microcells of subwavelength holes on an aluminum film

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(Received 26 November 2006; accepted 22 April 2007; published online 21 May 2007)

This investigation presents an observation of enhanced optical transmission through an Al film that is perforated with microcells that are arranged in random structures. The dispersion relations of the Al/p-Si surface plasmon polaritons in these structures with individual microcells with $3 \times 3$, $6 \times 6$, $9 \times 9$, $12 \times 12$, and $16 \times 16$ hole arrays of hexagonal were deduced. The transmission peak wavelength is determined from the spatial period of the microcell arrays. The random structure provides multicolor light transmission, which can be exploited in infrared wavelength-selective devices. © 2007 American Institute of Physics. [DOI: 10.1063/1.2740175]

Surface plasmons (SPs) in periodic metal structures have been widely studied. However, a question is raised regarding which peak position do SPs generate when the array of hole is nonordered. To answer this question, $N \times N$ hexagonal hole arrays (where $N$ is the number of isolated holes, $N = 3, 6, 9, 12, 16$) were arranged randomly on an aluminum (Al) film, and the characteristics of the transmission spectra and the dispersion relations of surface plasmon polaritons (SPPs) were investigated. The metal films herein in this investigation were prepared by depositing a 300-nm-thick Al layer on a doubly polished $p$-type silicon wafer ($p$-Si). The photoresist was spun onto Al films that were used as lithographic masks. Following pattern transfer, the microcells of holes were formed by wet etching. The lattice constant was in the range of $3\sim7 \mu$m. The radius of the holes was $1 \mu$m. The Al metal was perforated over an area of $1 \times 1 \mathrm{cm}^2$. The insets in Figs. 1 and 2 present the analyzed structure: each microcell comprises hexagonal arrays of $3 \times 3$, $6 \times 6$, $9 \times 9$, $12 \times 12$, and $16 \times 16$ hexagonal holes, arranged in random structures.

The transmission spectra were obtained using a Bruker IFS 66VS Fourier-transform infrared spectrometer. The zero-order transmission spectra were obtained using light that was normally incident onto the surface of the perforated Al film. The SP resonance modes were observed as the incident angle $\Omega$ of the radiation that was varied in steps of $1^\circ \sim 40^\circ$. The light was incident in the $z$ direction; the sample was defined to lie in the $(x,y)$ plane, and it was rotated around the $y$ axis, as displayed in Figs. 1–3, respectively. The wave number resolution of the transmission spectra was $8 \mathrm{cm}^{-1}$.

For a hole array of hexagonal with period $a$, the peak transmission wavelength $\lambda_{\text{max}}$ is given by

$$\lambda_{\text{max}} = a \left[ \frac{4}{3} \left( m^2 - mn + n^2 \right) \right]^{-1/2} \left( \frac{\varepsilon_d \varepsilon_m}{\varepsilon_d + \varepsilon_m} \right)^{1/2},$$

where $m$ and $n$ are integers, and $\varepsilon_d$ and $\varepsilon_m$ are the dielectric constants of the dielectric material and the metal, respectively. In the absence of SP interaction, the predictions of Eq. (1) agree closely with the measured position of the SP resonances displayed in Fig. 1 for various values of $m$ and $n$. The dielectric constants of air ($\varepsilon_{\text{air}} = 1$), metal ($\varepsilon_{\text{Al}} = -6.93 \times 10^3 \pm 4.07 \times 10^3$ at a wavelength of $9.6 \mu$m (Ref. 5)), and the dielectric material (Si wafer; $\varepsilon_{\text{Si}} = 11.9$) differ significantly. As the angle of incidence is varied, the SP dispersion relation can be obtained. The propagation length of the SP wave is

$$L_{\text{SP}} = 2 \text{Im}(k_{\text{SP}}) \alpha$$

where

$$\alpha = \frac{\omega \varepsilon_m}{2 \varepsilon_m} \left( \frac{\varepsilon_m}{\varepsilon_{\text{air}} + \varepsilon_d} \right)^{3/2},$$

if $|\varepsilon_m| > |\varepsilon_d|$, a factor of 2 in the denominator of Eq. (2) must be deleted, where $C$ is the velocity of light and $\varepsilon_m$ ($\varepsilon_d$) is the real (imaginary) part of the Al dielectric constant ($\varepsilon_m$ $\varepsilon_d$) (Refs. 1 and 9). $L_{\text{SP}} = 0.9 \mathrm{cm}$ is obtained for Al at $\lambda_{\text{SP}} = 9.6 \mu$m, and $k_{\text{SP}} = k_{SP,x} + i k_{SP,y}$, represents the component of the complex SPP wave vector along the $x$ axis. The damping time $\tau_{\text{SP}}$ is linked via $\tau_{\text{SP}} = L_{\text{SP}} / v_{\text{ph}}$, where $v_{\text{ph}} = \omega / k_{\text{SP,y}} = 0.3 C$ is the phase velocity of SP. The intrinsic damping is determined by $k_{SP}$, and it is negligible because the (1,0) Al/Si transmission peak width that corresponds to a lifetime of $100 \mathrm{ps}$ in Fig. 1(a) is approximately $6.6 \times 10^{-5} \mathrm{eV}$, which is much less than the observed peak width, $\sim 4.3 \times 10^{-7} \mathrm{eV}$.

Figures 1(a)–1(d) present the zero-order transmission spectra for Samples in this series. Samples A, B, and C comprise lattice constants in the microcell with $a = 3$, 5, and $7 \mu$m, respectively. Sample D is a mixture of $N \times N$ microcell arrays ($N = 3, 6, 9, 12$) with various lattice constants $a = 3, 5,$ and $7 \mu$m; these are called $3, 5,$ and $7 \mu$m mixtures. The area ratio of the $a = 3, 5,$ and $7 \mu$m microcells to the entire metal film is 1:1:1. The radius of all of the subwavelength holes $r = 1 \mu$m in the microcell. Table I presents the structural parameters. Figure 1(a) displays the (1,0) Al/p-Si SP mode, which should appear at a wavelength of approximately $9 \mu$m based on Eq. (1); the measured value is $9.6 \mu$m, revealing a slight redshift from the theoretical value, which is associated with the radiation damping factor. The

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transmission peak comprises two peaks: the smaller on the left side at a wavelength of around 8 μm corresponds to the $\omega_+^+$ mode and the larger on the right side at a wavelength of 9.6 μm corresponds to the $\omega_-^-$ mode. This pair of peaks is produced by the Bragg scattering of SPPs in the periodic arrays of microcells, which yields two standing waves $\omega_+^+$ and $\omega_-^-$, and splits the peak into two peaks when the size of the hexagonal holes exceeds half of the lattice constant, $a/2$. According to Eq. (1), the degenerate (1,0) air/Al SP modes should appear at a wavelength of around 2.6 μm; the measured value is 2.8 μm, slightly redshifted from the theoretical value. This result is also attributable to the radiation damping factor. Figure 1(b) reveals that the (1,0) Al/Si SP mode appears at a wavelength of about 15 μm; the measured value is 15.4 μm, slightly redshifted from the theoretical value. The (1,−1) and (2,0) Al/Si SP modes appear at 8.6 μm.
and 7.5 μm, respectively. The (1,0) air/Al SP mode appears at a wavelength of about 5 μm; the measured value is 4.8 μm. Figure 1(c) indicates that the transmission intensity becomes weak and a high-order mode appears because the hole areas are only 7.4% of the total area, and the transmitted intensity becomes weaker as the lattice constant declines in a periodic array or an N×N array.\textsuperscript{3,10} Figure 1(d) shows that the transmission intensity increased with the size of the holes, such as a=3 and 5 μm. The peak wavelengths of the transmission spectrum (λ\textsubscript{max}) were 9.6 and 15.4 μm, corresponding to the (1,0) Al/p-Si SP mode of samples A and B, respectively.

Figures 2(a)–2(c) present the transmission spectra of samples A, B, and D by rotating the samples around the y axis. As displayed in Fig. 2(a), as the incident angle increases, the six degenerate (1,0) Al/Si surface plasmon modes split into four modes, depending on the axis of symmetry, and even higher-order modes can be identified.\textsuperscript{10} Hence, the (1,0) Al/Si SP modes, which include six degenerate [(1,0), (−1,0), (1,1), (0,1), (0,−1), and (−1,−1)] Al/Si SP modes, and the (−1,−1) Al/Si mode are redshifted as Ω is increased, while the (1,1) Al/Si mode is blueshifted. The (0,1) and (1,0) Al/Si modes are degenerate and slightly blueshifted. The (0,−1) and (−1,0) Al/Si modes remain degenerate and slightly redshifted. Figure 2(b) presents the transmission spectra from sample B. The degenerate (1,0) Al/Si SP modes split into four modes as the incident angle Ω increases. The (1,0) air/Al modes behave similarly. The four \([-1, -1), (2,1), (-2, -1), \) and \((1, -1)\) Al/Si modes, identified collectively as the (1,−1) Al/Si mode, are also degenerate at normal incidence. The (1,−1) and (2,0) Al/Si modes are slowly redshifted as the angle Ω increases. Figure 2(c) presents the transmission spectra of samples D. The (1,0) Al/Si SP modes of microcells with lattice constants of 3 and 5 μm are present at 9.6 and 15.4 μm, but those with a=7 μm are absent. They all behave similarly to those displayed in Figs. 2(a) and 2(b).

Figure 3 presents the SPP dispersion relations of sample B and corresponds to the peaks of Fig. 2(b). Six degenerate (1,0) Al/Si surface plasmon modes (≈0.083 eV) and the even higher-order modes are observed, which also depict the dispersion relations for (1,−1) and (2,0) Al/Si modes and the (1,0) air/Al mode. The degenerate (1,−1) Al/Si modes split into four \([-1, -1), (2,1), (-2, -1), \) and \((1, -1)\) SP modes and the degenerate (2,0) Al/Si modes split into six \([(2,0), (0,2), (2,2), -2, 0), (0, -2), \) and \((-2, -2)\) SP modes, but the latter splits are not clearly shown in Fig. 3 because of the weak intensity of SP. No coupling to the waveguide modes of the SP that propagates between the microcells exists: coupling resonance modes of SPs are not observed in this series of experiments.

In summary, the periodicity of subwavelength holes in a random arrangement of microcell arrays determines the peak wavelength of the transmission spectrum, λ\textsubscript{max}. The multiple samples allow multipeak transmission when microcells with different lattice constants are added, transmitting multicolored light, which can be exploited in wavelength-selective infrared devices.

The authors would like to thank the National Science Council of the Republic of China, Taiwan for financially supporting this research under Contract No. NSC 94-2120-M-002-013.


**TABLE I.** Structural parameters and position of surface resonance for samples A, B, C, and D. (unit: μm): x: the intensity of SP resonance is weak.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lattice constant of microcell</th>
<th>Hole radius of microcell</th>
<th>Theoretical position</th>
<th>Measured position</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3</td>
<td>1</td>
<td>9</td>
<td>9.6</td>
</tr>
<tr>
<td>B</td>
<td>5</td>
<td>1</td>
<td>15</td>
<td>15.4</td>
</tr>
<tr>
<td>C</td>
<td>7</td>
<td>1</td>
<td>21</td>
<td>21.2</td>
</tr>
<tr>
<td>D</td>
<td>Mix (3,5,7)</td>
<td>1</td>
<td>(9, 15, 21)</td>
<td>(9.6, 15.4, x)</td>
</tr>
</tbody>
</table>