Surface plasmon-enhanced amorphous-silicon-nitride light emission with single-layer gold waveguides

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Surface-plasmon (SP) enhancement of amorphous-silicon-nitride (a-SiNₓ) light emission with single-layer gold (Au) waveguides is experimentally demonstrated through time-resolved photoluminescence measurement. The a-SiNₓ active layer with strong steady-state photoluminescence at 560 nm is prepared by plasma-enhanced chemical vapor deposition, and the Au waveguide on the top of the a-SiNₓ layer is fabricated by magnetron sputtering. The maximum Purcell factor value of ∼3 is achieved with identified SP resonance of the Au waveguide at ∼530 nm.

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Silicon light emitters have attracted great attention due to the compatibility of optoelectronic integration with the standard complementary metal oxide semiconductor (CMOS) processes[1,2]. In order to achieve practical silicon light emitters, various nano-structured silicon materials, including porous silicon, silicon oxide (SiOₓ) and silicon nitride (SiNₓ), have been proposed and demonstrated[3–8]. However, the emission efficiency of such materials is still much lower than that of III–IV semiconductors[9–14]. Surface plasmon (SP) is a promising way to improve spontaneous emission (SE), due to its large density of states for photons and the small mode volume of the electromagnetic field (i.e., SP mode). In our previous work, several approaches have been proposed for SP-enhanced Si light emitters, including single/double-layer metal waveguide, cermet waveguide, and metallic grating[15–19]. In the current work, the single-layer metal waveguide approach is experimentally demonstrated with the active material of SiNₓ. We adopted SiNₓ due to its lower potential barriers compared with SiOₓ; this characteristic facilitates the carrier injection of electrically-pumped devices. A gold (Au) waveguide is fabricated on top of the SiNₓ active layer by magnetron sputtering, after which the SP enhancement is evaluated through time-resolved photoluminescence (TRPL) measurement. The maximum value of measured Purcell factor (PF) is ∼3.

In our experiments, the steady-state photoluminescence (SSPL) and TRPL measurements were performed using a photoluminescence spectrometer (FLSP920, Edinburgh Instrument) equipped with a 450-W steady state xenon lamp (Xe900) and a nanosecond flash lamp (nF900). Firstly, a series of amorphous-silicon-nitride (a-SiNₓ) samples with different SSPL peaks in the range of 450 to 700 nm were prepared on the silicon substrates. This process was completed by plasma-enhanced chemical vapor deposition (PECVD, L-450P CVD System, Anelva), using SiH₄ and NH₃ or N₂ as the reactant gas sources. The measured SSPL spectra at the excitation wavelength of 325 nm for the three typical samples (A to C, respectively) are shown in Fig. 1, and their deposition conditions are given in Table 1. The difference in emission peaks of a-SiNₓ may arise from amorphous silicon nano-clusters with varied average sizes of <3 nm[20,21]. In principle, the central emission wavelength of SiNₓ should be consistent with the SP resonance wavelength of Au (∼530 nm) in order to achieve the maximum SE enhancement. However, in order to distinguish the SP resonance from original SSPL, sample B with the SSPL peak at 560 nm was utilized to demonstrate the emission peak caused by the SP resonance. Although such arrangement can lead to the deterioration of the PF, it is helpful in identifying the SP resonance. The refractive index of sample B was measured to be 1.99 at 630 nm by an ellipsometer. Subsequently, a thin Au film was sputtered on the top of the a-SiNₓ sample with Au target (99.99%) and pure conditions are given in Table 1. The difference in emission peaks of a-SiNₓ may arise from amorphous silicon nano-clusters with varied average sizes of <3 nm[20,21]. In principle, the central emission wavelength of SiNₓ should be consistent with the SP resonance wavelength of Au (∼530 nm) in order to achieve the maximum SE enhancement. However, in order to distinguish the SP resonance from original SSPL, sample B with the SSPL peak at 560 nm was utilized to demonstrate the emission peak caused by the SP resonance. Although such arrangement can lead to the deterioration of the PF, it is helpful in identifying the SP resonance. The refractive index of sample B was measured to be 1.99 at 630 nm by an ellipsometer. Subsequently, a thin Au film was sputtered on the top of the a-SiNₓ sample with Au target (99.99%) and pure

Fig. 1. SSPL of three different plasma-enhanced chemical vapor deposited a-SiNₓ samples from A to C at the excitation wavelength of 325 nm.

Table 1. PECVD Conditions of a-SiNₓ Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiH₄ (sccm)</th>
<th>N₂ (sccm)</th>
<th>NH₃ (sccm)</th>
<th>Temperature (°C)</th>
<th>Pressure (Pa)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>9</td>
<td>0</td>
<td>10</td>
<td>RT</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>B</td>
<td>9</td>
<td>0</td>
<td>10</td>
<td>300</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>C</td>
<td>4</td>
<td>80</td>
<td>0</td>
<td>300</td>
<td>70</td>
<td>150</td>
</tr>
</tbody>
</table>

Note: RT stands for room temperature.
same a-SiN \(_x\) with a 15-nm-thick Au waveguide. For comparison, the age of sample B with thickness of 67 nm was also prepared.

Figure 2 shows the cross-sectional scanning electron microscope (SEM, S-5500, Hitachi) image of the coated sample with 30-nm Si and 15-nm Au layers. Therefore, it is reasonable that the measured SSPL peaks around 530 nm originate from the SP resonance of the Au waveguides.

In order to evaluate the SP enhancement, photoluminescence (PL) lifetimes of all the samples were measured with TRPL. The PF can be calculated with the definition of PF = \(\tau / \tau^*\), in which \(\tau\) is the original PL lifetime and \(\tau^*\) is the enhanced one.[22] Figure 6 shows the TRPL spectra (thin line) with the fixed excitation/detection wavelength of 325 nm/560 nm. The fitted curves using the following double exponential function (thick line) were also plotted[23]. The function is given as

\[
R(t) = a_0 + a_1 e^{-t/\tau_1} + a_2 e^{-t/\tau_2},
\]

where \(\tau_1\) and \(\tau_2\) are the two dominant decay times representing the recombination of electron-hole pairs (excitons) with two different lifetimes of around one and a few nanoseconds in a-SiN \(_x\), respectively, \(a_1\) and \(a_2\) are the pre-exponential factors, and \(a_0\) is the additional background. The descending edges of the fitted curves for both coated samples are steeper than those of the uncoated sample, indicating decreased PL lifetimes or the improved spontaneous emission rates. With the measured values of \(\tau_1\) and \(\tau_2\), the average lifetime \(\langle \tau_{ave} \rangle\) can be calculated through the following equation:

\[
\tau_{ave} = b_1 \tau_1 + b_2 \tau_2,
\]

where \(b_1\) and \(b_2\) are the relative PL intensities \((a_1 \tau_1/(a_1 \tau_1 + a_2 \tau_2) \times 100\%, i = 1 \text{ or } 2)\) of the first and second decay times, respectively.

Figure 4 shows the calculated density of states (DOS) of both coated a-SiN \(_x\) samples with single-layer Au waveguides where the peak wavelengths of the coated samples are much lower than that of the uncoated one. In addition, the peak wavelength of the uncoated sample is 560 nm, whereas the SSPL peak wavelengths of the coated samples with 15 and 25 nm Au are almost the same as 530 nm (Fig. 3). For a deeper insight, the density of states (DOS) of each coated sample was calculated based on the formula of \(d(\beta^2)/d(h\omega)\). In this formula, \(\beta\) is the propagation constant, \(h\) is the reduced Planck’s constant, and \(\omega\) is the angular frequency.[17] The maximum DOS values of both Au waveguides are the same \((\sim 2.2 \text{ eV})\), and they are very close to the measured SSPL peak position \((\sim 530 \text{ nm/\sim 2.3 eV})\) of the coated samples (Fig. 4). Meanwhile, the SP resonance can be red-shifted by increasing the ambient effective refractive index above the Au waveguide; this can be achieved by coating it with a higher index material and/or increasing its thickness.[16] A thin Si film was sputtered on the 15-nm-Au-coated sample with Si target (99.99%) in order to observe the peak shift. By increasing the Si thickness from \(\sim 15\) to \(\sim 30\) nm, the SSPL peak position of the coated sample is red-shifted to the original one (560 nm) of the uncoated sample (Fig. 5). The inset of Fig. 5 is the cross-sectional SEM image of the coated sample with 30-nm Si and 15-nm Au layers.

Fig. 2. Cross-sectional scanning electron microscope image of the a-SiN \(_x\) sample coated with a 15-nm-thick Au waveguide.

Fig. 3. SSPL of the a-SiN \(_x\) samples without and with single-layer Au waveguides (thicknesses of 15 and 25 nm, respectively) at the excitation wavelength of 325 nm.

Argon gas (99.999%). Figure 2 shows the cross-sectional scanning electron microscope (SEM, S-5500, Hitachi) image of sample B with thickness of \(\sim 367\) nm and coated with a 15-nm-thick Au waveguide. For comparison, the same a-SiN \(_x\) sample with a 25-nm-thick Au waveguide was also prepared. Then, the SSPL spectra of all the samples (without/with single-layer Au waveguides) were measured while the excitation light with the wavelength of 325 nm was incident from the Au-coating side (Fig. 3). Here, the spectra were normalized to recognize the peak positions. Given that the excitation light is partly reflected outside by the Au films, the measured SSPL intensities of the coated samples are much lower than that of the uncoated one. In addition, the peak wavelength of the uncoated sample is 560 nm, whereas the SSPL peak wavelengths of the coated samples with 15 and 25 nm Au are almost the same as 530 nm (Fig. 3). For a deeper insight, the density of states (DOS) of each coated sample was calculated based on the formula of \(d(\beta^2)/d(h\omega)\). In this formula, \(\beta\) is the propagation constant, \(h\) is the reduced Planck’s constant, and \(\omega\) is the angular frequency.[17] The maximum DOS values of both Au waveguides are the same \((\sim 2.2 \text{ eV})\), and they are very close to the measured SSPL peak position \((\sim 530 \text{ nm/\sim 2.3 eV})\) of the coated samples (Fig. 4). Meanwhile, the SP resonance can be red-shifted by increasing the ambient effective refractive index above the Au waveguide; this can be achieved by coating it with a higher index material and/or increasing its thickness.[16] A thin Si film was sputtered on the 15-nm-Au-coated sample with Si target (99.99%) in order to observe the peak shift. By increasing the Si thickness from \(\sim 15\) to \(\sim 30\) nm, the SSPL peak position of the coated sample is red-shifted to the original one (560 nm) of the uncoated sample (Fig. 5). The inset of Fig. 5 is the cross-sectional SEM image of the coated sample with 30-nm Si and 15-nm Au layers. Therefore, it is reasonable that the measured SSPL peaks around 530 nm originate from the SP resonance of the Au waveguides.
second exponential components as a percentage, respectively. The average PF can be obtained by dividing the average lifetime of the uncoated sample ($\tau$) by that of the Au-coated sample ($\tau^*$). The calculated average lifetimes and the PFs are plotted in Fig. 7, with varied detection wavelengths ranging from 530 to 560 nm. The average lifetimes of the coated samples are shorter, and the corresponding PFs range from 1.2 to 3.2. In addition, a little larger PF is achieved with the thicker coating (25 nm) (Fig. 7(b)), though our simulation results indicate that the DOS and the corresponding PF with the thicker coating would be smaller than those with the thinner coating. Such disparity between the experimental and calculated data has yet to be explained, and the reason behind it remains unclear. At present, we are still working on the possible (joint) influence of metal waveguide properties, including thickness, surface morphology and crystalline state to the SP enhancement. However, according to the experimental results, the SP enhancement of single-layer Au waveguides for the Si light emitter is experimentally demonstrated when the maximum PF value of ~3 is achieved. Considering the propagation loss of the SP mode on the smooth waveguide, the PF can be further enhanced by adopting rough waveguides to scatter SP modes into free space before significant depletion.

In conclusion, we fabricate a series of a-SiNx samples through PECVD with strong SSPL in the range of 450 to 700 nm. Based on the selected sample with the SSPL peak wavelength of 560 nm, the SP resonance of Au at ~530 nm is experimentally demonstrated through the SSPL measurement. Furthermore, the SP enhancement of single-layer Au waveguides for the a-SiNx spontaneous emission is observed through the TRPL measurement, and the maximum PF value of ~3 is obtained. The experimental results indicate that metal waveguides can serve as simple alternatives in improving the SE of Si light emitters.

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References