Surface-plasmon-induced light absorption on a rough silver surface

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We investigate light absorption in metal films, silver and aluminum, with different surface roughness. Measurements using an integrating sphere show that the reflectance in silver decreases significantly with increasing surface roughness whereas the reflectance in aluminum is almost constant. The experimental results agree well with numerical simulations in which the surface roughness of metal is described properly. In particular, the simulations demonstrate that the absorption by surface-plasmon-polaritons excited on a rough silver surface causes the surface-dependent reflectance in silver. This study suggests a convenient and feasible rule to rationally design a backside metal reflector toward high-efficiency light-emitting diodes and photovoltaics. © 2011 American Institute of Physics. [doi:10.1063/1.3537812]

High-reflectivity metal reflectors are used widely to demonstrate high-performance optoelectronic devices such as lasers, light-emitting diodes (LEDs), and photovoltaics. Recently, nanopatterned metallic structures have also been investigated to effectively extract photons or excite surface-plasmon-polaritons (SPPs). However, the fact that the reflectivity in real or nanopatterned metals tends to decrease with increasing surface roughness can create unexpected problems in optical applications requiring high reflectivity. Thus far, only a few reports have considered light absorption by unavoidable or intentional surface roughness in metals. In this study, we systematically examine light absorption in silver and aluminum with different surface roughness.

In the case of a normal incidence of light from a dielectric material with a refractive index of nd to a metal with a refractive index of nm +iε, the reflectance R becomes

\[ R = \frac{1}{1 + \frac{4n_d}{(n_d-n_m+i\epsilon)(n_d+n_m+i\epsilon)}^2} \] (Ref. 10).

If the wavelength of incident light is 450 nm and the dielectric material is sapphire (nd = 1.78), the reflectance by silver and aluminum are 97.0% and 87.4%, respectively. Silver is typically used as an efficient reflector in the visible and infrared wavelengths owing to its high reflectance. However, the dielectric-metal interface was assumed to be perfectly flat in this simple analysis. In a real metal, surface roughness should be considered because it is detrimental to its reflectivity. For example, the excitation of SPPs on a roughened metal surface can be one of the main origins of light absorption in metals.

To quantify the effect of surface roughness on light absorption in metal films, we measured reflected and diffused light in silver and aluminum with different surface roughness using an integrating sphere. Sapphire substrates were first prepared with three different surface roughnesses. A sapphire substrate, which is transparent in the visible wavelength, was used to control the surface roughness of a dielectric-metal interface. Sapphire surfaces with root-mean-square (rms) roughness of 1, 7, and 13 nm were fabricated by polishing mechanically the front side of sapphire using slurries with grain sizes of 0.5, 3, and 6 μm, respectively, as shown in the atomic force microscopy (AFM) images in Figs. 1(a)–1(c). Silver or aluminum with a thickness of 200 nm was then evaporated on the front side of each sapphire substrate. Since metal is deposited conformally along the surface of a dielectric substrate, the roughness of the dielectric-metal interface is solely determined by that of sapphire. Reflected light on the sapphire-metal interface was measured, as shown in Fig. 1(d). A halogen lamp with a fixed incident angle of 5° and covering all visible wavelengths from 350 to 700 nm was used as the incident light source. All diffused photons in addition to reflected ones with the same incident angle were collected using a silicon photodetector inside the integrating sphere.

The reflectance of the silver (red) and aluminum (black) substrates measured at an incident wavelength of 450 nm were plotted as a function of the rms roughness of each metal [Fig. 1(e)]. If the surface is flat (rms roughness = 1 nm), silver would have greater reflectance than aluminum according to the above equation. However, the reflectance of silver decreased significantly with increasing roughness, whereas the reflectance of aluminum decreased only slightly. Eventually, as the rms roughness was > 10 nm, silver has lower reflec-

![Image](https://via.placeholder.com/150)

**FIG. 1.** (Color online) (a), (b), (c) AFM images of sapphire substrates with rms roughness of 1, 7 and 13 nm, respectively. (d) Schematic of the experimental setup for the reflectance measurement. (e) Measured reflectance as a function of rms roughness.

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tance than aluminum. Although it has been known that the reflectivity of silver is superior to that of any metal in the visible wavelength range, a surface roughness of even a few-nanometers causes a substantial deterioration in the reflectivity of silver. Therefore, when silver is used as a reflector of an optoelectronic device, it is essential to minimize the surface roughness of the dielectric substrate for silver to be deposited to achieve higher performance. Otherwise, other metals, such as aluminum, would be more suitable for a roughened interface in terms of reactivity.

Three-dimensional (3D) finite-difference time-domain (FDTD) simulations were performed to better understand this reflectance behavior (Fig. 2). The interaction between the normally incident plane wave and a single nanopattern with a cone shape at the metal-sapphire interface was first examined to highlight the effect of a single object in terms of exciting SPPs. Both the width and height of the cone were defined as d [Fig. 2(a)]. To present the experimental situation of Fig. 1(e), planewaves with a wavelength of 450 nm were normally incident to the metal surface from the sapphire. Figure 2 shows that silver and aluminum had quite different features. For example, at d = 50 nm, silver showed strong electric field intensity inside the nanopattern [Fig. 2(a)] but electric field intensity was not penetrated into aluminum [Fig. 2(d)]. At such a relatively large d, some incident light is converted into SPPs at the rough silver surface. The SPPs are absorbed by the silver, which eventually decreases the reflectance. On the other hand, one can expect that aluminum, where SPPs are barely excited, retains its original reflectance at the same surface roughness.

The absorption power density (log J-E) is a fairly good representation of the absorption loss by SPPs, as shown in Figs. 2(b) and 2(e). SPPs were excited locally, even at small d in silver (d = 10 nm), and propagated along the silver-sapphire interface [Fig. 2(b)]. Figure 2(c) shows integration of Fig. 2(b) along the vertical direction, which is the absorption power per unit surface area normalized by the intensity of the incident planewave at each d. The absorption power density was increased significantly by localized SPPs around the nanopattern as much as by the long-range propagating SPPs over the entire surface [Fig. 2(c)]. In particular, SPPs propagating along the surface, the oscillation pattern in Fig. 2(c), emerged more clearly at d = 50 nm. On the other hand, no SPPs were excited in all d’s in aluminum [Fig. 2(e)] and the magnitude of surface-dependent absorption was suppressed dramatically [Fig. 2(f)]. In the case of aluminum, light is absorbed in the entire surface regardless of the existence of a nanopattern due to the large plasma oscillation frequency of aluminum. Note that the offset of the absorption power density in aluminum is higher than that in silver, which suggests that the intrinsic material loss of aluminum is still larger than that of silver.

Randomly dispersed nanopatterns at the metal-sapphire interface were introduced in the FDTD simulation to emulate the rough metal surfaces actually fabricated (Fig. 3). In Fig. 3(a), the reflectance in silver (red) and aluminum (black) were calculated as a function of the rms roughness of the metal surfaces which were defined in the FDTD. This simulation strongly supports the measured values shown in Fig. 1(e). Although silver has higher reflectance at rms roughness = 0 nm, the reflectance of silver decreases significantly with increasing rms roughness and becomes lower than that of aluminum at a rms roughness > 1 nm. Note that this rms roughness, ~1 nm, at which silver has a lower reflectivity than aluminum, is different from the rms roughness measured in Fig. 1(e), ~10 nm. This discrepancy is due to the identical cone shape of the nanopatterns introduced in the FDTD [inset of Fig. 3(a)]. It will be necessary to introduce distribution of the shapes of the nanopatterns in the simulation for more accurate comparison with the measurement. The electric field intensity profiles (log|E|^2) calculated at rms roughness = 8 nm also clearly show that a number of incident photons are coupled and absorbed along the corrugated surface of silver more than aluminum [Figs. 3(b) and 3(c)]. Consequently, the light absorption by SPPs in silver causes a significant decrease in reflectivity with increasing surface roughness.

It is important to select a proper high-reflectivity backside reflector to extract more photons in LEDs. Although silver is used conventionally because of its high reflectivity at an optically flat surface, silver does not always provide the
best reflectivity unless the dielectric-silver interface is extremely smooth. To demonstrate this aspect through practical devices, six GaN LEDs were fabricated with different bottom reflectors in terms of metal and its roughness [Fig. 4(a)]. Silver and aluminum were used as a backside reflector onto a dielectric substrate with different surface roughness and output powers from these LEDs were measured. As shown in Fig. 4(b), the output powers in the LEDs with silver (red) and aluminum reflectors (black), at a standard current of 80 mA, were plotted as a function of the rms roughness. In accordance with the above analyses [Figs. 1(e) and 3(a)], the output power in the LED with the silver reflector decreased radically with increasing rms roughness. On the other hand, a relatively small change in the output power was observed in the LED with an aluminum reflector. This agreement also confirms that roughness-dependent absorption is still valid in such omnidirectional light applications. The same trend was observed from lower to higher current injection. The electrical properties were unchanged regardless of the metal and surface roughness. Therefore, to maximize the output powers of LEDs and avoid plasmon-induced absorption loss, it is essential to prepare an ultrasmooth dielectric substrate for silver to be deposited.

In summary, this study measured the reflectance of silver and aluminum with different surface roughness, and showed that the SPPs excited on a rough silver surface cause significant absorption that reduces the reflectance. This is an important step toward the demonstration of high-power LEDs and high-efficiency photovoltaics with a proper backside metal reflector.

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