Silicon colors: spectral selective perfect light absorption in single layer silicon films on aluminum surface and its thermal tunability

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Abstract: Using two most abundant materials in nature: silicon and aluminum, spectral selective perfect light absorption in single layer silicon films on aluminum surface is demonstrated. Perfect light absorption is achieved due to the critical coupling of incident optical wave to the second order resonance mode of the optical cavity made of a thin silicon film on aluminum surface. Spectral selective perfect light absorption results in different optical colors corresponding to different thicknesses of silicon films. The device colors do not change when viewing from large angles with respect to the surface normal. Perfect absorption wavelength can be tuned over a wide wavelength range over 70 nm by thermal annealing. This new technology, which is low cost and compatible with silicon technology platform, paves the way for many applications such as optical color filters and wavelength selective photodetectors.

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References and links


1. Introduction

Spectral selective light absorption in thin semiconductor films can be used for optical color filters and photodetectors. Recently, spectral selective light absorption in ultrathin germanium films on a gold surface was reported in the visible range of spectrum [1]. However, the absorption in the ultrathin germanium films on metal surface is not complete. To make perfect absorption, a strategy of adding a thin dielectric layer on top of the semiconductor films was reported [2, 3]. More complicated perfect light absorption nanostructures have also been investigated in the visible range [4–7]. In the infrared range, spectral selective perfect light absorption has been investigated in thin film structures such as vanadium dioxide films on sapphire [8], doped silicon films on sapphire [9], and germanium films on heavily doped silicon substrate [10, 11]. The strong light absorption in ultrathin semiconductor films is caused by the first order optical resonance mode and the large phase delays at two boundaries of the semiconductor thin films.

In the past decade, silicon has been a material extensively investigated for photonics applications [12, 13]. Silicon is one of the most abundant materials on the earth and it has relatively low cost compared with other semiconductor materials [14]. In this work, we choose silicon on aluminum to realize spectral selective perfect light absorption and optical color filters. The silicon-on-aluminum perfect light absorber consists of a silicon thin film deposited on a thick aluminum film surface. By increasing the thickness of the silicon film, multiple optical resonance modes can be supported. Completely light absorption occurs when the critical coupling condition happens to the second order optical resonance mode of the thin film optical cavity. Spectral selective perfect light absorption in the devices results in vivid optical colors under ambient light illumination. With thermal annealing, optical constants of sputtered silicon films are changed, which results in the color changes of the perfect light absorbers.

2. Silicon on aluminum perfect light absorber structure

Figure 1 illustrates the thin film perfect light absorber device profile that consists of a single layer silicon film of thickness \(d\) on a thick aluminum film surface. The aluminum film is thick enough that blocks light transmission. The structure is an asymmetric Fabry-Perot (FP) optical cavity, also called the Gires-Tournois cavity [15]. Here, silicon is chosen because silicon is a low cost material and has been widely used in electronics industry for several decades. Most importantly, silicon has the smallest optical extinction coefficient among all commonly used high index semiconductor materials in the visible range. Figure 2 shows the refractive index \((n)\) and extinction coefficient \((k)\) of several most common semiconductor materials [16, 17]. It can be seen that crystalline and polycrystalline silicon materials have smallest extinction coefficients compared with other semiconductor materials in the visible range. This property makes silicon the best choice of materials for making optical interference devices such as optical filters in the visible and near infrared spectral range.
In this work, we choose aluminum as the substrate metal layer material underneath silicon films because aluminum has excellent metallic optical property in the short wavelength range of the visible spectrum. Also aluminum is one of the most abundant materials on the earth and has relatively low cost compared with other metals such as gold or silver.

Fig. 1. Schematic of the silicon on aluminum thin film perfect light absorber structure.

Fig. 2. Optical constants of several most common semiconductor materials. (a) Indexes of refraction and (b) extinction coefficients [16, 17].

Optical reflectance from a single layer silicon film on aluminum metal surface structure shown in Fig. 1 can be calculated by using optical wave interference theory. The optical reflectance is $R = |r|^2$, where $r$ is the optical wave reflection coefficient given by [18]

$$r = \frac{r_{12} + r_{23}e^{-2j\varphi}}{1 + r_{12}r_{23}e^{-2j\varphi}}. \quad (1)$$

In Eq. (1), $r_{12}$ and $r_{23}$ are Fresnel reflection coefficients of the optical wave from medium 1 (air) to medium 2 (silicon) and from medium 2 (silicon) to medium 3 (aluminum), respectively. $\varphi = k_2 d$ is the phase delay of the optical wave in the silicon film of thickness $d$. For TE polarization incidence, $r_{12}$ and $r_{23}$ are

$$r_{12} = \frac{k_1 - k_2}{k_1 + k_2}, \quad r_{23} = \frac{k_2 - k_3}{k_2 + k_3}. \quad (2)$$

For TM polarization incidence, $r_{12}$ and $r_{23}$ are

$$r_{12} = \frac{n_2^2k_1 - n_1^2k_2}{n_2^2k_1 + n_1^2k_2}, \quad r_{23} = \frac{n_3^2k_2 - n_2^2k_3}{n_3^2k_2 + n_2^2k_3}. \quad (3)$$
In Eqs. (2) and (3), \( k_1y, k_2y, k_3y \) are the normal components of the wave vectors inside air, silicon film, and aluminum substrate respectively. The normal components of the wave vectors can be calculated as
\[
k_n = k_0\sqrt{(n_i^2 - n_i^2 \sin^2(\theta))^{1/2}},
\]
where \( \theta \) is the angle of incidence in the air, \( n_i \) is the index of refraction of the medium \( i (i = 1,2,3 \) for air, silicon, and aluminum respectively), \( k_0 \) is the free space propagation constant. For unpolarized light, the optical reflectance is the averaged optical reflectance of TE and TM polarizations.

3. Experimental and simulation results

In fabricating silicon film perfect light absorbers, we first deposited a 300 nm thick aluminum film on a 4-inch Pyrex glass wafer by using a Denton sputter. The Argon plasma pressure was 5 mTorr and the DC power was 200 watt during sputtering. It took 1880 seconds to deposit 300 nm aluminum film. After the aluminum film was deposited, the wafer was diced into 20 pieces with 0.5 by 0.5 inch for each piece. Then, silicon films with thickness varying from 10 nm to 200 nm were sputtered on each piece with 10 nm increment. The Argon plasma pressure was 5 mTorr and the RF power was 200 watt during the sputtering. The pre-sputtering time was 180 seconds for stabilizing the deposition rate. The deposition rate of silicon was 0.083 nm per second. Silicon films of different thicknesses were obtained by varying the sputtering time. Silicon and aluminum film thicknesses were measured by using a surface profilometer (KLA-Tencor P10).

Figure 3(a) shows photographs of the fabricated devices taken under fluorescent ambient light illumination. The thicknesses of silicon thin films are indicated next to each device. It can be seen that these devices have different colors corresponding to different silicon film thicknesses. Yellow color is seen for silicon film thickness of 20 nm and is seen again for silicon film thickness of 80 nm. As the thickness of silicon film increases from 20 nm to 40 nm, the color of the device changes from yellow to red, and to grey. As the thickness of silicon film changes from 80 nm to 120 nm, the color changes from yellow to purple, and to blue. Slightly increasing the silicon film thickness to 130 nm, the color of the device changes from blue to green.

It was reported earlier that thermal annealing can change sputtered silicon films from amorphous phase to polycrystalline phase and therefore change the optical properties of silicon films [19]. The phase change from amorphous silicon to polycrystalline silicon significantly reduces the imaginary part of the refractive index of silicon films. To examine the effect of thermal annealing, all samples were thermally annealed in a furnace (Thermolyne 48000) with a starting temperature of 25°C, a ramp rate of 30°C per minute, and an annealing temperature of 600°C for 10 minutes in an Argon environment. Figure 3(b) shows the photographs of the devices after thermal annealing. The colors of the devices have changed because of the thermal annealing.

Optical reflectance spectra of the fabricated devices were measured with an optical spectrometer (StellarNet C-SR-50) and an unpolarized broadband halogen light source. The angle of incidence of the light is 10° from the surface normal. The optical reflectance is obtained by normalizing the reflection from the device to the reflection from a glass wafer, and then multiplying the optical reflectance from the glass wafer. The optical reflectance from the glass wafer is 7% due to the reflection from the top and bottom two surfaces. Figures 4(a)-4(d) show the measured optical reflectance spectra from the devices of silicon film thickness from 10 nm to 200 nm with 10 nm increment before thermal annealing. In the range of silicon film thickness from 20 nm to 80 nm, only one optical resonance mode is seen in the visible spectral range in Figs. 4(a) and 4(b). This is the first order Fabry-Perot optical resonance mode in the thin film optical cavity. As the thickness of silicon film increases to 90 nm and above, another optical resonance mode appears in the visible spectral range. This resonance mode is the second order Fabry-Perot optical resonance mode. The second order optical
resonance mode results in perfect absorption in devices with silicon film thickness from 110 nm to 140 nm as shown in Fig. 4(c).

![Fig. 3. Photographs of the silicon thin films on aluminum surface (a) before thermal annealing and (b) after thermal annealing. Silicon film thickness increases from 10 nm to 200 nm with 10 nm increment as indicated beside each device. Devices with silicon film thickness between 110 nm and 140 nm can completely absorb light in wavelength range of 500 nm-700 nm. After thermal annealing, the peak absorption wavelengths shifted to shorter wavelengths and the colors of the devices changed accordingly.](image)

The first order optical resonance occurs in devices with silicon film thickness from 20 nm to 80 nm. At the first order optical resonance mode, light absorption in the device is not complete as shown in Figs. 4(a) and (b), because the thicknesses of silicon films are too thin that the absorption in the optical cavities is less than the coupling loss from the air to the cavity. This explains that strong optical light absorption occurs in the ultrathin germanium films on gold surface, but the absorption is not complete [1]. As the thickness of silicon film increases, the thin film optical cavity supports multiple optical resonance modes. Among these multiple resonance modes, one resonance mode can meet the critical coupling condition. The critical coupling condition is a condition that the optical power coupled from air to the device equals to the optical loss per resonance cycle in the optical cavity [20, 21]. The second order resonance mode of the thin film optical cavity can meet the critical coupling condition because of the increased silicon film thickness. The second order optical resonance mode appears in the visible spectral range when the silicon film thickness increases to 90 nm and above. At the second order optical resonance mode for silicon film thickness from 110 nm to 140 nm, critical coupling condition can be met, and perfect light absorption occurs in the wavelength range of 552 nm - 700 nm as shown in Fig. 4(c). The peak absorption wavelengths are 552 nm, 605 nm, 657 nm and 700 nm for the silicon films with thickness of 110 nm, 120 nm, 130 nm, and 140 nm. In this silicon film thickness range, the optical absorption of all devices is more than 99% at their second order optical resonance wavelengths. By increasing the silicon thickness, the peak absorption wavelength shifts to longer wavelength. The third order optical resonance mode starts to appear in the visible spectral range as the silicon thickness reaches to 150 nm and above as shown in Fig. 4(d). However, the third order optical resonance mode cannot cause complete light absorption in the thin film optical cavity because the coupling loss is less than the absorption loss per resonance cycle in the optical cavity.
Fig. 4. Measured reflectance spectra of the fabricated devices: (a-d) before thermal annealing and (e-h) after thermal annealing. Perfect light absorption was achieved in 110-140 nm-thick silicon films within the spectral range of 552 nm-700 nm (c) before thermal annealing and (g) shifted to the spectral range of 500 nm-635 nm after the thermal annealing.

After thermal annealing, we measured optical reflectance spectra from all the devices. Figures 4(e)-4(h) show the measurement results. For silicon film thickness of 110-140 nm,
critical coupling of the incident light into the silicon film results in complete light absorption within the wavelength range from 500 nm to 625 nm as shown in Fig. 4(g). For the silicon film thickness of 110 nm, 120 nm, 130 nm and 140 nm, the absorption peak wavelengths are at 500 nm, 531 nm, 587 nm and 625 nm, respectively. In this thickness range, the optical absorption in the annealed devices is more than 98%.

By comparing the measured optical reflectance before thermal annealing shown in Figs. 4(a)-4(d) and after thermal annealing shown in Figs. 4(e)-(h), it can be seen that the peak absorption wavelengths have blue-shifts. For example, the peak absorption wavelength had blue shifts of 52 nm, 74 nm, 70 nm, and 75 nm for the devices with silicon thickness of 110 nm, 120 nm, 130 nm, and 140 nm, respectively. The absorption wavelength shift causes the change of the colors as it can be seen in Figs. 3(a) and 3(b).

We plot 2D plots of optical reflectance versus the wavelength and the silicon film thickness with measurement data. The 2D plot of optical reflectance before thermal annealing is shown in Fig. 5(a) and the 2D plot of optical reflectance after thermal annealing is shown in Fig. 5(b). It can be seen that three optical resonance modes exist in the visible range as the silicon film thickness increases to 200 nm. Clearly, only the second order optical resonance mode results in perfect light absorption because only in this mode, the critical coupling condition can be met. For the first order resonance mode, the absorption loss is less than the coupling loss into the optical cavity. For the third order resonance mode, the absorption loss is larger than the coupling loss into the optical cavity.

During thermal annealing, the peak absorption wavelengths shifted to shorter wavelengths due to the change of the refractive index of the silicon films. We fitted the peak absorption wavelength as a linear function of the thickness of silicon film and indicate the fitted lines as the white dash lines in Fig. 5. Before annealing as shown in Fig. 5(a), the peak absorption wavelength of the first order optical resonance mode is \( \lambda_1 = 15d + 100 \) (nm) for silicon film of thickness \( d \) from 20 nm to 80 nm. The peak absorption wavelength of the second optical resonance mode is \( \lambda_2 = 4.2d + 106 \) (nm) for thickness \( d \) from 90 nm to 200 nm. The peak absorption wavelength for the third optical resonance mode is \( \lambda_3 = 2.5d + 100 \) (nm) for thickness changing \( d \) from 160 nm to 200 nm. After thermal annealing as shown in Fig. 5(b), the peak absorption wavelength of the first order resonance mode is \( \lambda_1 = 10d + 100 \) (nm) for thickness \( d \) from 30 nm to 90 nm. The peak absorption wavelength for the second order resonance mode is \( \lambda_2 = 4.1d + 31 \) (nm) for \( d \) from 100 nm to 200 nm. Finally, the peak absorption wavelength of the third order optical resonance mode is \( \lambda_3 = 2.5d + 50 \) (nm) for thickness \( d \) from 160 nm to 200 nm.

We calculated the optical reflectance versus wavelength by using the optical wave interference theory and also finite-difference time-domain (FDTD) simulation, respectively. Measured optical constants of sputtered silicon films before and after thermal annealing were used for the calculations. The FDTD simulation results agree well with the results calculated by using optical wave interference theory. This indicates that optical wave interference theory is still valid for nanometer scale ultrathin films. Figure 5(c) and Fig. 5(d) show the optical reflectance spectra calculated by using Eq. (1) before and after thermal annealing respectively. The results are in good agreement with the measurement results before thermal annealing shown in Fig. 5(a) and after thermal annealing shown in Fig. 5(b). The peak optical absorption wavelengths of the first order optical resonance mode shown in Fig. 5(c) for amorphous silicon film devices are fitted as a linear function of the thickness of silicon film. The fitted equation is \( \lambda_1 = 13.3d + 133 \) (nm), where both wavelength and silicon film thickness \( d \) have the unit of nanometer (nm) and the range of \( d \) is from 20 nm to 80 nm for fitting the first order resonance mode. The fitted linear function of the peak absorption wavelengths of the second order resonance mode is \( \lambda_2 = 4.4d + 70 \) (nm) where the range of \( d \) is from 90 nm to 200 nm. The fitted linear function of the peak absorption wavelengths for the third order optical resonance mode is \( \lambda_3 = 2.7d + 26 \) (nm) where \( d \) is from 160 nm to 200 nm. Calculation results of the absorption in annealed silicon film devices of different film
thicknesses are shown in Fig. 5(d). We also fit the peak absorption wavelengths of polycrystalline silicon films on aluminum optical cavities as linear functions of the silicon film thickness. It is found that the peak absorption wavelength of the first optical resonance mode is \( \lambda_1 = 12d + 40 \) (nm) for \( d \) from 30 nm to 90 nm. The fitted function of the peak absorption wavelengths of the second order optical resonance mode is \( \lambda_2 = 4.3d + 15 \) (nm) for \( d \) from 100 nm to 200 nm. The silicon film thickness is about 1/5 of the peak absorption wavelength. The fitted function for the third optical resonance mode is \( \lambda_3 = 2.2d + 70 \) (nm) for \( d \) from 160 nm to 200 nm.

![Fig. 5. 2D plots of the measured optical reflectance versus wavelength and silicon film thickness (a) before thermal annealing and (b) after thermal annealing. 2D plots of calculated optical reflectance versus wavelength and silicon film thickness for (c) amorphous silicon film devices and for (d) polycrystalline silicon film devices. White dash lines indicate the fitted peak absorption wavelength versus silicon film thickness for three optical resonance modes.](image)

We also calculated the percentages of light absorbed in silicon films and in aluminum at the peak absorption wavelengths of three optical resonance modes. The absorption in silicon film is calculated from the optical power reflectance from the device and the optical power transmittance across the silicon/aluminum boundary. We calculated the optical absorption in three devices at three optical resonance wavelengths: 50 nm amorphous silicon film device at the first order optical resonance wavelength, 130 nm amorphous silicon film device at the second order optical resonance wavelength, and 190 nm amorphous silicon film device at the third order optical resonance wavelength. At the first order optical resonance mode of the 50 nm thick silicon device at its peak absorption wavelength of 810 nm, 62% of the energy is absorbed in the silicon film and 19% is absorbed in the aluminum substrate. The total absorption is 81%. For the second optical resonance mode of the 130 nm thick silicon film device at the peak absorption wavelength of 657 nm, 88% of the light is absorbed in the silicon film and 12% is absorbed in the aluminum. The total absorption in the device is 100%. For the third order optical resonance mode of the 190 nm thick silicon film device at the peak absorption wavelength of 570 nm, 85% of the light is absorbed in the silicon film and 4% is absorbed in the aluminum. The total absorption light in this case is 89%. Also, it is found that as the silicon film thickness increases, light absorption in aluminum decreases.
Perfect light absorption in silicon films on aluminum can be explained with optical wave interference theory as discussed in [1, 8]. Since the silicon films are thin, perfect light absorption can also be explained as the result of the cancellation of the electric dipole polarizations in the silicon films and on aluminum metal surface. Because the light induced electric dipole polarization on metal surface is in the opposite direction of the electric dipoles in the silicon film, a quadruple electric resonance mode occurs on the silicon and aluminum boundary, which results in the cancelation of the backward radiation in the reflection.

4. Angular dependence of perfect light absorption

To investigate angular dependence of the silicon-on-aluminum perfect light absorbers, the devices were mounted on a rotational stage for measuring the angular dependence of optical reflectance. The incident light is unpolarized light from halogen light source. We verified that our optical spectrometer is insensitive to the polarization state of light. Four perfect light absorber devices made of 110 nm, 120 nm, 130 nm and 140 nm-thick sputtered amorphous silicon films on aluminum surface were measured in our experiment. Optical reflectance spectra were measured at different angles of incidence from 10° to 70° with 10° increment. The results are plotted and shown in Figs. 6(a)-6(d). It can be seen that by increasing the angle of incidence, the optical reflectance increases, the peak absorption wavelengths shift slightly to shorter wavelengths, but the reflection peak wavelength does not shift as the incident angle increases to 60°. Therefore, the colors of the devices remain unchanged when they are viewed from different angles. The angular insensitivity observed for the perfect light absorber devices is similar to what was reported for ultrathin germanium film light absorbers [1], in which light absorption is caused by the first order optical resonance mode.

Fig. 6. Optical reflectance spectra measured at different angles of incidence from 10° to 70°. Reflectance measured from the perfect absorber devices with silicon thickness of (a) 110 nm, (b) 120 nm, (c) 130 nm, and (d) 140 nm.
5. Conclusion

We have experimentally demonstrated perfect light absorption in sputtered single layer silicon thin films on an aluminum surface. The perfect light absorption is wavelength selective in the visible spectral range. By increasing the silicon thickness from 10 nm to 200 nm, fabricated devices exhibit different colors. Perfect light absorption occurs when the silicon film thickness falls in the range from 110 nm to 140 nm. Within this range, the incident light can be critically coupled into the second order optical resonance mode of the thin film optical cavity. The effect of thermal annealing on fabricated devices was also investigated. By thermal annealing, sputtered amorphous silicon films change phase to polycrystalline silicon films. The associated change of optical properties of sputtered silicon films causes the shift of the absorption wavelength to a shorter wavelength and causes corresponding color change. A 70 nm tunable range of perfect absorption wavelengths was measured for our perfect light absorbers. In addition, angular dependence measurement was carried out for our perfect light absorbers. Measurement results show that the peak optical reflectance wavelength in the blue side of the perfect absorption wavelength is insensitive to the change of incident angle up to 60° and the peak absorption wavelength has very small blue shifts as the angle of incidence increases up to 60°. The colors of the devices do not change when they are viewed from large angles with respect to the surface normal. Silicon and aluminum are two most abundant materials on earth. They are relatively low cost and are widely used in the electronics industry. The demonstrated spectral selective perfect light absorber technology paves the way for many practical applications such as low cost optical color filters, enhanced photodetectors, solar cells, and colorimetric biochemical sensors.

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