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PASSIVE NIGHTTIME RADIATIVE COOLING USING BLACK SILICON

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ABSTRACT. Decarbonized and low energy technologies for heat management and conversion are a key milestone for climate change mitigation. Cooling is one of the major fields where such technologies are required. Passive radiative cooling in its nighttime and daytime versions is therefore a promising technology to achieve those goals. We consider in this work a silicon based nanostructured material with outstanding visible and infrared radiation absorption and emission capabilities, Black Silicon (BSi), as a candidate for nighttime passive radiative cooling. We compare BSi with its flat silicon counterpart and different depths of BSi nanostructuration with respect to their radiative cooling power. We show that BSi cooling power is significantly larger than that of flat silicon by a factor up to 1.8 at 30°C with a cooling power of 75 W /m² and 140 W/m² for flat and black Silicon, respectively.

1. INTRODUCTION

Global warming is undoubtedly the main humanity challenge for the 21st century. One solution to address this challenge is to increase the use of low carbon energy resources. Solar or heat energy recovery are one of these resources. Devices to harvest and convert these resources, such as thermoelectric devices, thermal solar panels and passive radiative coolers, have been an active field of research during the past decade.

Passive radiative cooling takes benefit of the atmospheric transparency window between 8 and 13 μm , to cool down a system without energy input, thanks to the radiative thermal exchange between the system of interest and the cold space at 3K. Passive radiative cooling can be implemented in both nighttime and daytime scenarios but different materials properties are required depending on the considered situation. Such materials can be used for cooling and refreshing the human body, buildings, for harvesting dew water [1] or for electricity generation [2]. For an urban area, nighttime radiative cooling can be very interesting to mitigate the urban heat island effect for example. Several materials [3] have been recently developed for this purpose for both nighttime [1] and daytime radiative cooling [4-8]. For the latter, in addition to a large emissivity in the spectral range of thermal radiation, mid infrared for instance, a large reflectivity in the solar radiation spectral range is also required.

In this work, we present a silicon based micro and nano-structured material named black silicon (BSi) which exhibits a very large emissivity and absorptivity in the visible range that makes it appear black to the naked eye. In recent years, we have studied the morphology of this randomly nano-structured silicon fabricated using cryogenic deep reactive etching and the influence of its morphology, the doping level, the doping profile and surface functionalization on the material radiative properties [9—11]. We have shown that these different parameters enable to significantly enhance the material absorptivity and emissivity over a wide mid-infrared spectral range which make BSi a very good candidate for passive nighttime radiative cooling.

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In this paper, we calculate the radiative cooling power of different samples of BSi based on experimentally measured radiative properties we recently obtained. We show that the cooling power of BSi is significantly increased compared to flat silicon over a wide temperature range up to a factor 1.8 at 30°C with a cooling power of 75 W/m² and 140 W/m² for flat and black Silicon, respectively. We also extend the radiative power calculations to non-fabricated samples using simulated radiative properties validated with respect to the experimental data which enables us to discuss the effect of the micro and nano-structured silicon morphology as well as the effect of room temperature on the radiative cooling power.

2. METHODOLOGY

2.1 Black Silicon

Black Silicon is a well-established micro-nano-structured silicon surface that can be obtained by different techniques including cryogenic plasma as considered in this work. BSi exhibits fascinating wetting and optical properties. In particular, due to its specific morphology, it is well-known for its excellent absorption of almost 100% of incident light, hence its name is Black according to its color to the naked eye (Figure 1 left). We have recently shown that we can extend such outstanding properties to the mid-infrared (MIR), up to 15 μm, by using highly doped silicon or by modifying the material nano-micro-structures morphology [11] (Figure 1 right).

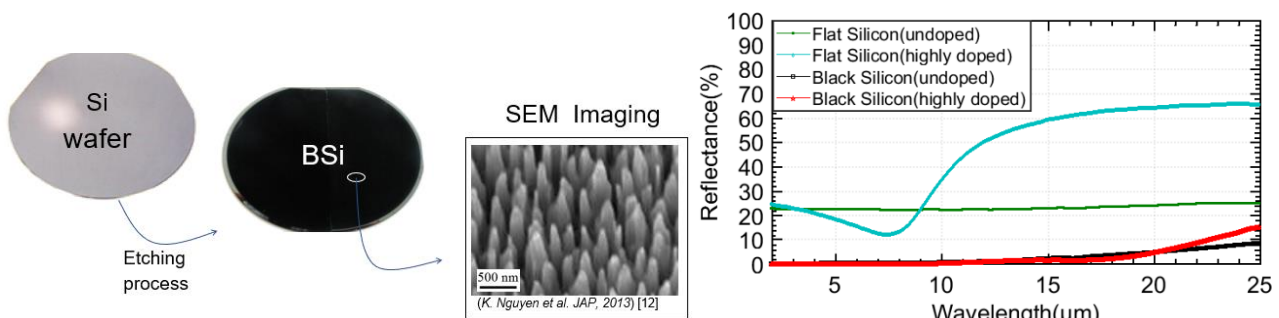


Figure 1. (Left) Silicon wafer processing to turn it Black[12]. (Right) Spectral reflectance as a function of wavelength comparing undoped BSi and highly doped BSi, as well as two flat samples taken as a reference for both undoped and highly doped cases. All measurements were done at ambient temperature.

2.2 Methods of calculations

We use the main laws of radiation in our calculations. The net radiative cooling power P_{cool} is obtained by the difference between the power P_{rad} emitted by our sample towards outer space and the power P_{atm} absorbed from the environment as well as the convective and conductive power gained from the surrounding medium $P_{cond+conv}$, as given by Ref. [4, 5].

$$P_{cool}(T) = P_{rad}(T) - P_{atm}(T_{amb}) - P_{cond+conv} \quad (1)$$

As we focus on night time, we do not consider any heating power that could come from sun energy. For the emitted radiative power from our sample, as described by equation (2), we consider the emissivity of our material as a function of wavelength and incidence angle $\varepsilon(\lambda, \theta)$. We take into account the spectral range for which we obtained experimental emissivity values, i.e. between 1,5 and 20 μm in our case. We also consider in a first approach that the emissivity is isotropic. Consequently, we take only $\varepsilon(\lambda)$ with the wavelength to calculate the angular integral of the hemisphere.

$$P_{rad}(T) = A \int d\Omega \cos\theta \int_0^\infty d\lambda I_{bb}(T, \lambda) \epsilon(\lambda, \Omega) \quad (2)$$

with A the surface and $I_{bb}(T, \lambda) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/(\lambda k_B T)} - 1}$, the blackbody irradiance.

The incident atmospheric radiation towards our sample generates an absorbed power, given by equation (3):

$$P_{atm}(T_{amb}) = A \int d\Omega \cos\theta \int_0^\infty d\lambda I_{BB}(T_{amb}, \lambda) \epsilon(\lambda, \theta) \epsilon_{atm}(\lambda, \theta) \quad (3)$$

where $\epsilon_{atm}(\lambda, \theta) = 1 - t(\lambda)^{1/\cos\theta}$ is the atmospheric emissivity, in which t represents the transmissivity of the atmosphere in the zenith direction according to [13]. Cooling performances highly depend on the atmospheric transmittance. Therefore, we choose a very detailed model, which takes into account the atmospheric window between 8 and 13 μm , but also the second window just below 20 μm .

The conductive and convective contribution can be estimated by a joint coefficient of convection and conduction. In a first approximation, we calculate the potential cooling power when the sample is at ambient temperature. In this case, conduction and convection heat fluxes are nil. When the sample temperature is different from the ambient, we assume a relative insulation of the sample to limit the conductive and convective thermal exchanges and therefore consider a joint convection and conduction coefficient of 6 $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$.

3. RESULTS AND DISCUSSION

If the net radiative cooling power is positive, it means that the temperature could go below its actual temperature. When $P_{cool}(T) = 0$, it means that the sample has reached the steady state temperature. It also means that without a variation of an external parameter, the temperature will not change. In our calculations, we consider different samples and we compare the net cooling power, which enables a sample's temperature to decrease below an ambient temperature of $T_{amb} = 30^\circ\text{C}$. We consider an ambient temperature of a hot situation that requires cooling, which can be observed under an urban "heat island" situation for example.

In Figure 2, we compare our reference flat silicon against BSi with 2 depths of the conical nanostructuring of BSi for which we performed absorptivity measurements ($d=4,2\mu\text{m}$ and $d=10,3\mu\text{m}$). We consider a mixed conductive and convective coefficient of 6 $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, when the sample temperature varies from the ambient temperature. We can see that the cooling power of BSi is greater than its flat Si counterpart. The steady-state temperature is also lower for BSi than for flat Si. The steady state temperature of flat silicon is around 21 $^\circ\text{C}$ in this configuration, while for both BSi samples, it is around 17 $^\circ\text{C}$. The performance of BSi with a larger depth $d=10,3\mu\text{m}$ is, as expected, slightly better than BSi with a depth of 4,2 μm due to the larger emissivity of the former.

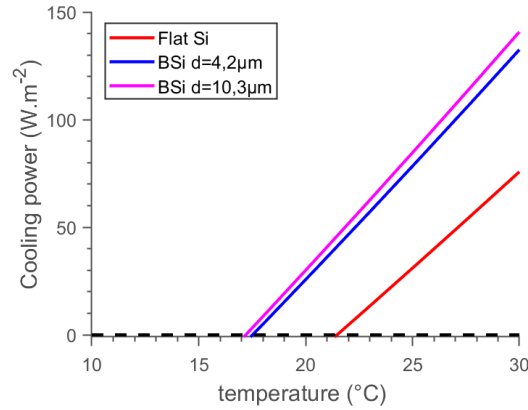


Figure 2. The cooling power of the three considered samples (two different BSi and one flat Si) as a function of its temperature for an ambient temperature of 30°C.

We also study the dependence of the potential cooling power of different BSi with different nano and micro-structures depths that can be obtained with different etching times. We have simulated the absorptance of BSi with different depths as a function of wavelength [11] as shown in the inset of Figure 3. The deeper the etching of BSi, the higher its absorptance and the wider its spectral range of large absorptance. It reflects directly on the potential cooling power of a sample at 30°C with an ambient temperature of 30°C. With a deeper etching, the potential cooling power is higher.

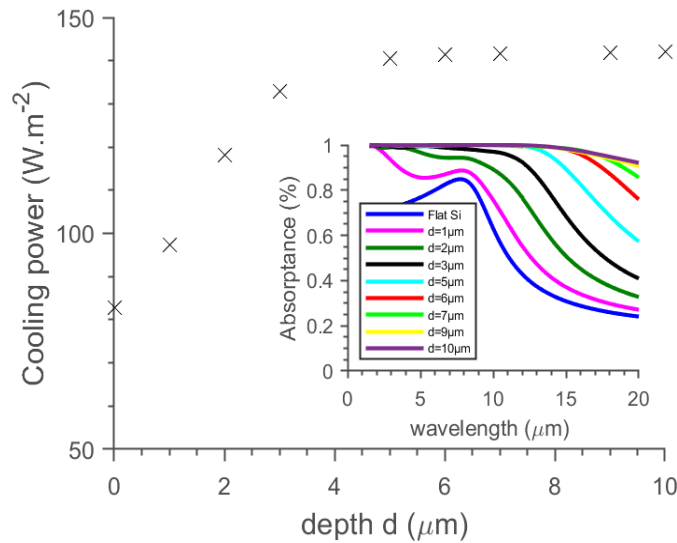


Figure 3. The potential cooling power of different BSi samples at 30°C as a function of the depth of the material nanostructuration for an ambient temperature of 30°C. Inset: Absorptance of BSi with different depths as a function of wavelength [11].

At last, in Table 1, we compare the potential cooling power of a sample at 30°C with ambient temperature of 30°C for Flat Si, BSi and an ideal material for daytime radiative cooling. This ideal material has an emissivity equal to 1 between 8 and 13μm in the atmospheric transparency window and equal to 0 outside. The ideal material has a lower potential radiative power than both BSi, but has also a reduced absorption of radiative power from the environment. So, depending on the studied conditions and chosen atmospheric transmissivity, BSi samples could have better initial potential cooling power.

Table 1: Comparison between Flat Si, BSi with 2 depths (4,2 μm and 10,3 μm) and an idealistic behavior.

	Flat Si	BSi d=4,2 μm	BSi d=10,3 μm	Ideal
$P_{cool}(W.m^{-2})$	75,74	132,49	140,75	128,20
$P_{rad}(W.m^{-2})$	173,70	309,76	345,96	157,00
$P_{atm}(W.m^{-2})$	97,96	177,27	205,21	28,80

6. CONCLUSION

BSi shows a promising potentiality for passive nighttime radiative cooling. BSi considered in this work is a better radiative cooler than flat silicon with a radiative cooling power increased by a factor up to 1.8 at 30°C, with a cooling power of 75 W/m² and 135 W/m² for flat and black silicon, respectively. We have also shown that depending on some parameters such as the conductive and convective effects, the atmospheric transmittance as well as the operation temperature, BSi could exhibit better results than a material with an ideal emissivity of 1 between 8 and 13 μm . Indeed, the considered atmospheric transmittance has a high influence on the radiative cooling power. A detailed study of this parameter impact is currently ongoing and will be published in a future work. Finally, increasing the BSi high emissivity selectivity and adapting it to the atmospheric transmittance spectral range is the next milestone to significantly improve this material performances for passive radiative cooling.

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