Visible Light Plasmonic Heating-Enhanced Electrochemical Current in Nanoporous Gold Cathodes

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Taking advantage of the localized surface resonance effect to boost the performance of electrochemical cells has rarely been demonstrated using nanoporous metal films as photoactive electrodes. Rather, studies on plasmon-enhanced electrochemical processes use plasmonic metal nanoparticles loaded onto semiconductor or conductor substrates. Here we present experimental evidence for the use of visible light to significantly enhance the kinetics of a redox reaction involving the oxidation of aluminum at the anode, and the reduction of hydrogen ions to hydrogen gas at the cathode. This reduction reaction is allowed to take place on a nanoporous Au film used as plasmonic photocathode. A 20-fold increase in the electrochemical current density was recorded upon exposure of the nanoporous Au cathode to visible light. We demonstrate that this significant current enhancement is associated with local heat generated in Au during localized surface plasmon resonance. These results could be exploited to develop high-performance heterogeneous photocatalysts based on plasmonic heating, for the conversion of renewable energy resources into fuels and value-added chemicals.

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Due to its high abundance, solar energy is expected to play a key role in meeting the 21st century energy challenges.1,2 A very promising approach to harvest sunlight involves the localized surface plasmon resonance (LSMR) effect, during which plasmon-induced hot carriers, electromagnetic fields, and heat generated in nanostructured metals are exploited for applications in photovoltaics, photodetection, photocatalysis and photothermal therapy.3,4,5,6,7,8,9,10 Although the LSMR effect has been demonstrated in three-dimensional (3D) monolithic nanoporous nanomaterials,6,11 taking advantage of this effect to enhance the rate of electrochemical processes has rarely been demonstrated using monolithically nanoporous metals as the photoactive component. Rather, previous studies have been limited to the enhancement via plasmonic metal nanoparticles.3,5,7 One advantage of monolithic nanoporous metals over their nanoparticle counterparts is the fact that nanoporous metal films can be readily used as self-supporting photovoltaic materials, whereas plasmonic metal nanoparticles are commonly used as composites, i.e. in combination with semiconductor or conductor supports. In such a composite configuration, it is not straightforward to take full advantage of phenomena such as visible light-induced heating, since the localized heat generated in plasmonic metal nanoparticles can readily dissipate in the support. Here we present experimental evidence for the use of visible light to significantly enhance the kinetics of chemical reactions taking place at the surface of a semiconductor-free monolithic 3D nanoporous metal. To demonstrate this concept, we choose to enhance the rate of a spontaneous redox reaction, namely the corrosion of Al metal in dilute acid. With a very negative standard reduction potential of −1.66 V vs SHE, Al metal can spontaneously corrode in acids. Based on the mixed potential theory of corrosion,20 Al dissolution in a non-oxidizing acid involves two half-reactions: (i) an oxidation reaction during which the corroding metal loses electrons and is converted into metal cation through the following reaction: Al (s) → Al3+ + 3e−; (ii) a reduction reaction during which hydrogen ions in the electrolyte gain these electrons to form hydrogen gas through the following reaction: H+ + e− → H2. Although common corrosion processes are based on microcell corrosion in which both the oxidation and reduction half-reactions take place on the same piece of metal (in our case Al metal),21 it is possible to dissociate these two half-reactions so that they take place on different materials (i.e. macrocell corrosion). In our work, we use this latter approach: the oxidation reaction takes place on a piece of Al metal (i.e. the anode), while hydrogen gas formation through the reduction reaction takes place on a piece of nanoporous Au (NP-Au) film (i.e. the cathode). In such a macrocell configuration, a direct measurement of the corroding current is possible. In the absence of any light, the corroding current density is on the order of 0.1 mA/cm2 (the area is that of the NP-Au film). When the NP-Au cathode is exposed to light, the corroding current density increases by more than one order of magnitude, from 0.1 mA/cm2 up to ~2 mA/cm2. We demonstrate that this significant current enhancement is attributed to plasmon-induced heat, in agreement with the temperature-dependent rate of chemical reactions as depicted by the Arrhenius equation.

Experimental

Synthesis of plasmonic nanoporous Au.—White Au leaves with average thickness ~100 nm and composition Au15Ag85 at. % (Noris Blattgold, Germany) were used for the synthesis of our NP-Au films by free corrosion dealloying in 15 M nitric acid at room temperature.14 Dealloyed leaves were left in the nitric acid bath for approximately 15 minutes before being rinsed four times in DI water. The corresponding monolithic NP-Au was deposited onto glass slides by floating the NP-Au in water and lifting the slide to catch the NP-Au.

Characterization.—Scanning electron microscopy (SEM) JEOL 7500 and transmission electron microscopy (TEM) JEOL 2010F were used to analyze the microstructure of the NP-Au films. The optical spectra of the NP-Au films were investigated using a standard spectrophotometer (Agilent Cary 5000).

Cell assembly and experimental setup.—Before cell assembly, the footprint area of each NP-Au cathode on glass slide was standardized to 2 cm × 2 cm, by physically wiping away excess material. (Note that since the corresponding footprint area was 4 cm2, all currents measured from our cell were divided by 4 to obtain the current density with as unit mA/cm2). Copper tape was used to make contact with the NP-Au film. A strip of filter paper was placed over the NP-Au electrode and extended into a 0.5 M sulfuric acid bath acting as a wick to provide the electrodes with a consistent supply of ions, and a separator to prevent a short circuit (see Figure 3). A piece of aluminum foil (the...
anode) was placed on top of this paper strip. Another glass slide was then placed on top of the aluminum foil and the whole cell was tightly clamped using bulldog clamps. The cell was mounted above a solution containing 0.5 M sulfuric acid to be wicked into the cell via the separator. A temperature probe was placed adjacent to the cell to measure the ambient temperature surrounding the cell during experimentation (see Figure 3). The positive lead of a TEK Power TP905BT multimeter was attached to the NP-Au electrode and the negative lead was attached to the aluminum electrode. After steady state corrosion was achieved in the absence of light, a solar simulator (Abet Technologies, Model LS 150) equipped with 150 W Xe Arc Lamp was placed 3 cm away from the cell to illuminate the NP-Au cathode. The intensity of light from this solar simulator was \( \sim 1.2 \text{ kW/m}^2 \) and the corresponding light intensity reach our cell (3 cm away from the cell) was estimated to be \( \sim 0.71 \text{ kW/m}^2 \).

### Results and Discussion

**Microstructural and optical characterizations.**—Typical dealloyed NP-Au films are shown on glass slide substrates in Figure 1a. The film thickness is \( \sim 100 \text{ nm} \). Details on the synthesis are found in the Experimental section. The scanning and transmission electron micrographs of Figures 1b and 1c respectively show the corresponding 3D bicontinuous porous microstructures. The characteristic ligament size from transmission electron micrographs data is around 30 nm.

Light interaction with the NP-Au films was investigated by UV-vis spectroscopy. In general, during light interaction with Au nanostructures, excited surface plasmons in the material decay by emitting photons (radiative decay) and electron-hole pairs (non-radiative decay).\(^{22,23}\) The typical absorbance (blue curve) and transmittance (red curve) spectra collected during light interaction with our NP-Au films are shown in Figure 2. During this UV-vis spectroscopy, the NP-Au film was immersed in 0.5 M H\(_2\)SO\(_4\) because subsequent photocurrent measurements were carried out using a similar acid solution (i.e., 0.5 M H\(_2\)SO\(_4\)) as the corroding medium to dissolve Al metal. The UV-vis spectra of our NP-Au films are similar to those reported previously in dealloyed NP-Au films,\(^{14,17,26}\) characterized by enhanced light transmission in the visible range with one dip in the transmittance spectrum around \( \sim 535 \text{ nm} \).\(^{14,17,26}\) Enhanced light transmission through porous films has been widely investigated since the report of Ebbesen et al. on the extraordinary optical transmission through sub-wavelength hole arrays.\(^{22}\) Based on recent understanding of light interaction with complex assemblies of nanostructures including plasmonic oligomers,\(^{27}\) porous films with sub-wavelength hole arrays as in refence,\(^{22,28}\) and metamaterials,\(^{29}\) the presence of a dip in the transmittance spectra of these nanostructured materials is associated with Fano-type resonance involving constructive and destructive interference in the system.\(^{30}\) This is also applicable to disordered nanoporous films and may justify the shape of the transmittance spectra in Figure 2, with a characteristic dip around 535 nm.

![Figure 1. (a) Synthesized NP-Au films on glass slide substrates. Typical (b) scanning and (c) transmission electron micrographs.](image)

**Photoelectrochemical current enhancement.**—Photoelectrochemical cells were assembled using NP-Au film as the cathode, Al foil as the anode and 0.5 M H\(_2\)SO\(_4\) as the electrolyte. The Al anode can spontaneously dissolve in 0.5 M H\(_2\)SO\(_4\) without any external electrical energy supply. A sketch of the setup is shown in Figures 3a (side view) and 3b (front view). In this cell configuration, the two half-reactions associated with the spontaneous corrosion of Al in 0.5 M H\(_2\)SO\(_4\) are dissociated in such a way that Al metal dissolves at the anode, while the counter reaction involving the reduction of H\(^+\) into H\(_2\) gas takes place on the NP-Au cathode. This makes it possible to measure the corrosion current density associated with the external flow of electrons between the anode and cathode, as illustrated in Figure 4a.

In the absence of any light, the corroding current density is on the order of 0.1 mA/cm\(^2\). When the NP-Au film is exposed to light, the corroding current density increases with more than one order of magnitude. The blue and red curves from Figure 4b represent two typical current density profiles recorded on two different cells when the NP-Au plasmonic photocathode is alternately exposed to light (solid arrows) and dark (open arrows). On average, the current density reversibly increases from 0.1 mA/cm\(^2\) (dark) up to \( \sim 2 \text{ mA/cm}^2 \) upon exposure to light. This 20-fold current density enhancement induced by light can be rationalized by plasmonic heating during the LSPR in the NP-Au photocathode. Indeed, it is well-established that a substantial amount of heat is locally produced during LSPR in metallic nanostructures, and this heat has been exploited in applications ranging from photothermal therapy,\(^{25,30,31}\) to localized steam generation.\(^{32,34}\) In the latter case, changes in water temperature up to \( \sim 150{\circ} \text{C} \) have been reported during steam generation using plasmonic Au nanoparticles.\(^{32}\) Santos et al. recorded a temperature increase on the order of 26°C upon laser irradiation of a substrate-bound nanoporous gold disk array in water.\(^{35}\) In our work, since the rate of chemical reactions is temperature-dependent through the classical Arrhenius equation, plasmonic heating in the NP-Au photocathode will enhance the reduction rate of H\(^+\) into H\(_2\). A key point in the mixed potential theory mentioned in the introduction is to the law of charge conservation: All electrons consumed during the reduction reaction on the NP-Au photocathode should be compensated by electrons generated through Al oxidation at
the anode. Hence, the increase in the reduction rate of $\text{H}^+$ into $\text{H}_2$ will cause the rate of Al oxidation to increase. This explains the overall enhancement in the photoelectrochemical current of the cell during exposure of the NP-Au photocathode to light.

**Contribution of non-plasmonic heat.**—The change in ambient temperature and heat from the light source used to excite surface plasmon in NP-Au have the potential to impact the measured photoelectrochemical current density. Therefore, in this section we investigate the contribution of non-plasmonic heat to the measured current density. To do so, the change in temperature associated with heat generated by the light source in the vicinity of the NP-Au film was recorded during the experiments. The typical heat profile is shown in Figure S1; the maximum change in temperature was found to be 7°C above room temperature. Next, to simulate the impact of the heat generated by the light source on the measured photoelectrochemical current, an electric heater was used to generate a similar temperature change of 7°C in the vicinity of the cell. Typically, the temperature change in the vicinity of our cell caused by heat from the solar simulator was initially recorded by a temperature probe adjacent to the cell (see Figure 3a) and found to be 7°C. Next in order to determine the impact of this external heat on the performance of our cell, an electric heater was used to generate the same change in temperature of 7°C in the vicinity of the cell, this time without solar simulator. In the meantime, the corroding current density was recorded. The current density was found to increase from 0.1 to $\sim$0.25 mA/cm² as the result of 7°C change in temperature without light exposure, as depicted by the red curve in Figure 4c. However, when comparing this change to the current density of 2 mA/cm² recorded when light was incident on the sample (see Figure 4c), it is reasonable to conclude that the change in amplitude due to external heat is negligible. In other words, the $\sim$20 times enhancement in current density during our experiments comes primarily from plasmonic heating associated with the LSPR effect in NP-Au. It is worth mentioning that the measured current density enhancement cannot come from other mechanisms such as hot electrons injection because the current increase during hot carriers transfer is usually very low, typically in the range of a few nA/cm² up to a few $\mu$A/cm², which is more than 3 orders of magnitudes lower than the 2 mA/cm² recorded in this work. It should also be clarified that the reported current enhancement cannot be attributed to possible temperature rise on the aluminum electrode, since heating the cell (including the aluminum electrode) in the absence of light does not result in the observed current enhancement. Furthermore, for the aluminum temperature to rise, heat needs to pass through the glass slide supporting the nanoporous gold film, then the...
nanoporous gold film and the separator, before reaching the aluminum electrode (see illustration in Figure 3b). This heat will most likely fully dissipate before arriving on the aluminum metal electrode.

**Required minimum heating.**—This section is aimed to estimate the theoretical minimum heat (i.e. minimum local increase in the NP-Au temperature) required to achieve the 20-fold photovoltaic current enhancement. To do so, we use the Butler-Volmer equation, which relates the measured current densities in the cell with and without light exposure to the corresponding reaction overpotentials and temperatures. The overpotentials needed in the Butler-Volmer equation were deduced from Evans diagrams (see Figure 5). Typically, the current densities measured in our cell in the absence (∼0.1 mA/cm²) and in the presence (∼2 mA/cm²) of light were used in combination with the reduction potentials associated with H⁺ reduction in acid (0.00 V vs SHE) and Al oxidation (−1.66 V vs SHE), together with literature values for the exchange current densities associated with H⁺ reduction on Au (∼10⁻⁶ A/cm²), and Al oxidation (∼10⁻¹⁰ A/cm²),⁵⁰ to estimate the corroding potential in the presence (−0.94 V vs SHE) and in the absence of light (−1.02 V), according to the mixed potential theory of corrosion (see Figure 5).⁴⁶ From these corroding potentials, the overpotentials involved in the process with and without light were determined and used in the Butler-Volmer equation to deduce the change in temperature needed to cause the corroding current to increase from ∼0.1 mA/cm² to −2 mA/cm² (see supporting information for analytical derivation). The minimum change in temperature for the NP-Au cathode was found to be 12°C above room temperature (see supporting information), which is a practical value in the sense that changes in temperature up to a few tens of degree can readily be achieved in metallic nanostructures during LSPR.⁵⁰,⁵¹ It should be emphasized that the 7°C change in temperature recorded earlier during non-plasmonic heating represents the heat in the vicinity of the cell. Due to heat dissipation across the cell components, one expects the effective change in temperature at the nanoporous Au/electrolyte interface to be lower than 7°C in the case of non-plasmonic heating. On the other hand, in the case of plasmonic heating, it is important to realize that the 12°C change in temperature estimated using the Butler-Volmer equation represents the theoretical minimum amount of heat needed to generate the 20-fold change in current density. In other words, the real change in temperature can be higher than 12°C. In fact, heat changes in water temperature up to ∼150°C have been reported during steam generation using plasmonic Au nanoparticles as mentioned previously.⁵²

**Conclusions**

In this work we have shown that visible light interaction with nanoporous gold can be exploited to enhance the rate of redox reactions. This was done using an electrochemical cell configuration consisting of Al metal used as the anode, dilute sulfuric acid used as the electrolyte, and a semiconductor-free nanoporous gold film used as a photocathode. The spontaneous dissolution of the Al anode in acid creates an electric current in the cell in the absence of light. Interestingly, when the nanoporous gold cathode was illuminated with visible light, a 20-fold increase in the cell current was recorded. This current enhancement was rationalized by plasmon-induced heat, which enhances the rate of the reduction reaction taking place on the nanoporous Au surface. Analytical study based on the Butler-Volmer equation was used to investigate the theoretical minimum temperature change in the Au electrode that can generate the observed 20-fold current enhancement. Plasmonic heating in monolithic nanoporous metal films could be exploited for applications in photocatalysis, to boost the kinetics of catalytic reactions using light.

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**References**

1. N. S. Lewis, G. Crabtree, A. J. Nozik, M. R. Wasielewski, and P. Alivisatos, “Basic Research Needs for Solar Energy Utilization,” *Basic Energy Sci. Work. Sol. Energy Util.*, 276, (2005).
2. N. S. Lewis, “Powering the Planet,” *MRS Bull.*, 32, 808 (2007).
3. C. Clavero, “Plasmonic-induced hot-electron generation at nanoparticle/metal-oxide interfaces for photovoltaic and photocatalytic devices,” *Nat. Photonics.*, 8, 95 (2014).
4. W. Hou and S. B. Cronin, “A review of surface plasmon resonance-enhanced photocatalysis,” *Adv. Funct. Mater.*, 23, 1612 (2013).
5. S. Peiris, J. McMurtie, and H.-Y. Zhu, “Metal nanoparticle photocatalysts: emerging processes for green organic synthesis,” *Catal. Sci. Technol.*, 6, 320 (2016).
6. X. Huang, P. K. Jain, I. H. El-Sayed, and M. A. El-Sayed, “Plasmonic photothermal therapy (PPTT) using gold nanoparticles,” *Lasers Med. Sci.*, 23, 217 (2008).
7. S. Linne, P. Christopher, and D. B. Ingram, “Plasmonic-metal nanostructures for efficient conversion of solar to chemical energy,” *Nat. Mater.*, 10, 911 (2011).
8. M. W. Knight, H. Sobhani, P. Nordlander, and N. J. Halas, “Photodetection with Active Optical Antennas,” *Science* (80-.), 322, 702 (2011).
9. H. M. Chen, C. K. Chen, C.-J. Chen, L.-C. Cheng, P. Wu, H. B. Cheng, Y. Z. Ho, M. L. Tseng, Y.-Y. Hsu, T.-S. Chan, J.-F. Lee, R.-S. Liu, and D. P. Tsai, “Plasmon inducing effects for enhanced photocatalytic water splitting: X-ray absorption approach to electronic structures,” *ACS Nano.*, 6, 7362 (2012).
10. S. Mubeen, J. Lee, W. R. Lee, N. Singh, G. D. Stucky, and M. Moskovits, “On the plasmonic photovoltaic,” *ACS Nano.*, 8, 8066 (2014).
11. H. A. Atwater and P. Polman, “Plasmonics for improved photovoltaic devices,” *Nat. Mater.*, 9, 205 (2010).
12. R. Sundaraman, P. Narang, A. S. Jernyn, W. A. G. Iii, and H. A. Atwater, “Theoretical predictions for hot-carrier generation from surface plasmon decay,” *Nat. Commun.*, 5, 1 (2014).
13. W. Lee, S. Muheen, G. D. Stucky, and M. Moskovits, “A surface plasmon enabled liquid-junction photovoltaic cell,” *Faraday Discuss.*, 178, 413 (2015).
14. E. Deti, M. Salverda, P. R. Onck, and J. T. M. De Hosson, “On the localized surface plasmon resonance modes in nanoporous gold films,” *J. Appl. Phys.*, 115, 044308 (2014).
15. X. Lang, L. Qian, P. Guan, J. Zi, and M. Chen, “Localized surface plasmon resonance of nanoporous gold,” *Appl. Phys. Lett.*, 98, 093701 (2011).
16. F. Yu, S. Ahl, A. M. Caminade, P. J. Majoral, W. Knoll, and J. Erlebacher, “Simultaneous excitation of propagating and localized surface plasmon resonance in nanoporous gold membranes,” *Anal. Chem.*, 78, 7346 (2006).
17. D. Jalas, L.-H. Shao, R. Canchi, T. Okuma, S. Lang, A. Petrov, J. Weiszmüller, and M. Eich, “Electrochemical tuning of the optical properties of nanoporous gold,” Sci. Rep., 7, 44139 (2017).
18. E. Detsi, S. Punzhin, P. R. Onck, and J. T. M. De Hosson, “Direct synthesis of metal nanoparticles with tunable porosity,” J. Mater. Chem., 22, 4588 (2012).
19. Q. Zhang, N. Large, P. Nordlander, and H. Wang, “Porous Au nanoparticles with tunable plasmon resonances and intense field enhancements for single-particle SERS,” J. Phys. Chem. Lett., 5, 370 (2014).
20. Z. Deng and E. Detsi, “Enhancing the free corrosion dealloying rate with a catalytically driven reaction,” Nano Lett., 9, (2017).
21. C. M. Hansson, A. Poursaee, and A. Laurent, “Macrocell and microcell corrosion of steel in ordinary Portland cement and high performance concretes,” Cem. Conc. Res., 36, 2098 (2006).
22. T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, P. A. Wolff, T. Thio, and P. A. Wolff, “Extraordinary optical transmission through sub-wavelength hole arrays,” Nature., 86, 1114 (1998).
23. D. Garoli, G. Ruffato, S. Cattarin, S. Barison, M. Perino, T. Ongarello, and F. Romanato, “Nanoporous gold—Application to extraordinary optical transmission of light,” J. Vac. Sci. Technol. B Microelectron. Nanom. Struct., 31, 012601 (2013).
24. K. Kolwas and A. Derkachova, “Damping rates of surface plasmons for particles of size from nano- to micrometers: reduction of the nonradiative decay,” J. Quant. Spectrosc. Radiat. Transf., 114, 45 (2013).
25. S. Link and M. A. El-Sayed, “Shape and size dependence of radiative, non-radiative and photothermal properties of gold nanocrystals,” Int. Rev. Phys. Chem., 19, 409 (2000).
26. G. Ruffato, F. Romanato, D. Garoli, and S. Cattarin, “Nanoporous gold plasmonic structures for sensing applications,” Opt. Express., 19, 13164 (2011).
27. M. Hentschel, M. Saliba, R. Vogelgesang, H. Giessen, A. P. Alivisatos, and N. Liu, “Transition from Isolated to Collective Modes in Plasmonic Oligomers,” Nano Lett., 10, 2721 (2010).
28. F. J. García-Vidal, L. Martín-Moreno, T. W. Ebbesen, and L. Kuipers, “Light passing through subwavelength apertures,” Rev. Mod. Phys., 82, 729 (2010).
29. B. Lu, Yanchuk, N. I. Zehudev, S. A. Maier, N. J. Halas, P. Nordlander, H. Giessen, and C. T. Chong, “The Fano resonance in plasmonic nanostructures and metamaterials,” Nat. Mater., 9, 707 (2010).
30. S. Lal, S. E. Clare, and N. J. Halas, “Nanoshell-enabled photothermal cancer therapy: Impending clinical impact,” Acc. Chem. Res., 41, 1842 (2008).
31. J. G. Morton, E. S. Day, N. J. Halas, and J. L. West, “Nanoshells for photothermal cancer therapy,” Methods Mol. Biol., 624, 101 (2010).
32. O. Neumann, A. S. Urban, J. G. Morton, S. Lal, P. Nordlander, and N. J. Halas, “Solar vapor generation enabled by nanoparticles,” ACS Nano., 7, 42 (2013).
33. Z. Fang, Y. R. Zhen, O. Neumann, A. Polman, F. J. García De Abajo, P. Nordlander, and N. J. Halas, “Evolution of light-induced vapor generation at a liquid-immersed metallic nanoparticle,” Nano Lett., 13, 1756 (2013).
34. L. Zhou, Y. Tan, D. Ji, B. Zhu, P. Zhang, J. Xu, Q. Gan, Z. Yu, and J. Zhu, “Self-assembly of highly efficient, broadband plasmonic absorbers for solar steam generation,” Sci. Adv., 2 (2016).
35. G. M. Santos, F. Zhao, J. Zeng, and W. C. Shih, “Characterization of nanoporous gold disks for photothermal light harvesting and light-gated molecular release,” Nanoscale., 6, 5718 (2014).
36. Z. Deng and E. Detsi, “Enhancing the free corrosion dealloying rate with a catalytically driven reaction,” Nano Lett., 13, 1023 (2013).