Exploiting the aluminum nitride bandgap for water separation and light-enhanced evaporation

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Abstract. The aluminum nitride bandgap energy matches the binding energy between salt and water molecules. Here we study the effect of 405-nm light on the rates of evaporation when saline solutions are imbibed within a porous ceramic aluminum nitride wick. Sensitive measurements are taken in a self-referencing setup and compared with the capillary fluid response. Evaporation rates increase with light illumination when the solution is more saline in a manner that indicates interfacial charge-transfer characteristics. Our results show consistent trends and strong potential for photonic environmental applications in salt-water separation processes.

1 Introduction

Aluminium nitride (AlN) possesses desirable optical and optoelectronic properties particularly for ultraviolet light applications. AlN is an electric insulator with a wide bandgap energy of 6 eV and has a high refractive index. Additionally, AlN is good thermal conductor[1] and a phononic epsilon-near-zero material in the atmospheric transmission window [2, 3]. Mechanically, AlN is hard ceramic with a low thermal expansion coefficient. It is hydrophilic, which means that it has a strong tendency to wick and adhere to water. This combination of properties with AlN presents interesting prospects, particularly as the binding energy between salt and water molecules is also approximately 6 eV.

We are interested in the combined opportunities associated with the capillary response of hydrophilic porous ceramics like AlN for water treatment, separation chemistry, and evaporative cooling processes. For example, in hot and dry climates, evaporative or "swamp" coolers are advantageous (capable of producing temperature differences as large as 25C with a small fan, for example). However, these water-based technologies are not feasible if there is also a water shortage or drought, of course. Therefore, we explore the potential for light-induced interfacial responses that may break salt-water bonds in capillary porous hydrophilic materials, since salt-water is in general, plentiful. While salt and water bond strongly, they may be preferentially separated photonic interactions. Our results also identifies opportunities for materials harvesting and environmental cleanup technologies.

We study the effect of 405-nm light on AlN particles. In similar work, second-harmonic deep-UV light is generated in a metasurface of ZnO particles [4]. Others have also observed that the nonlinear response of AlN thin films increases as the wavelength of the light decreases below 400 nm (which is double the bandgap energy) [5]. This points to a nonlinear response, which may drive a charge-transfer and water separation mechanism. The advantage of such an interfacial approach is that it exploits the bandgap and selectively transfers energy to the salt-water bond without high-entropy heating. Deep UV (DUV) light already has widespread water separation applications [6]. However, to the best of our knowledge, this is the first demonstration of the use of a highly reflective, large-bandgap wicking ceramic material to produce DUV light for water separation.

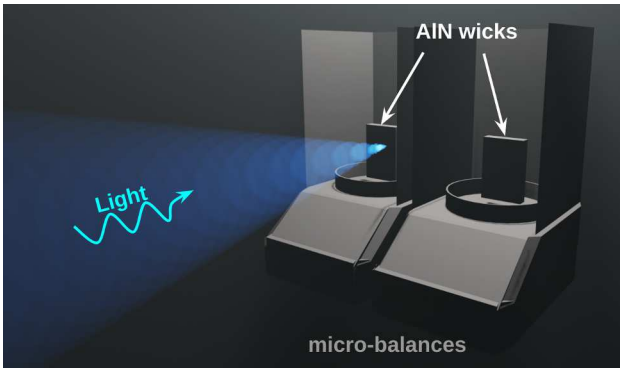

Figure 1. A 405 nm violet light, with irradiance of 100 $mW{\cdot}cm^{-2}$ is focused onto an AlN wick which sits in a reservoir of brine on top of a continuous-output micro-balance. Simultaneously, an identical wick/brine system (sans the light) is measured on an adjacent micro-balance, separated by a glass shield.

2 Experimental Methods

Experiments are sensitive to air currents and changes in humidity, so we use a self-referenced setup with two mi-

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crobalances [Fig. 1. The 405-nm LED with output irradiance of $35 - 100mW \cdot cm^{-2}$. We use a hygrometer to measure and control the ambient relative humidity, which we maintain between 30-35% prior to initiating experiments. All equipment is placed in an isolated, sealed acrylic box, which is covered in welding cloth to shield from ambient light. Light is focused onto a wick made from drop-cast AlN on an aluminum substrate. The capillary response of the wick is characterized. The wick is illuminated at normal incidence, and placed in a 40-mL reservoir of brine (10-30 wt% NaCl in deionized water). The mass is recorded continuously with a precision microbalance. Simultaneously, an identical setup with a sample and without light is placed adjacent inside the same box with a glass shield placed between the two balances to prevent cross-interference from convection currents. Afterwards, the experiment runs for 900 minutes. Simple background evaporation with no light or salt is used as a reference to determine the effectiveness of our wick under varying intensities of light and salinity.

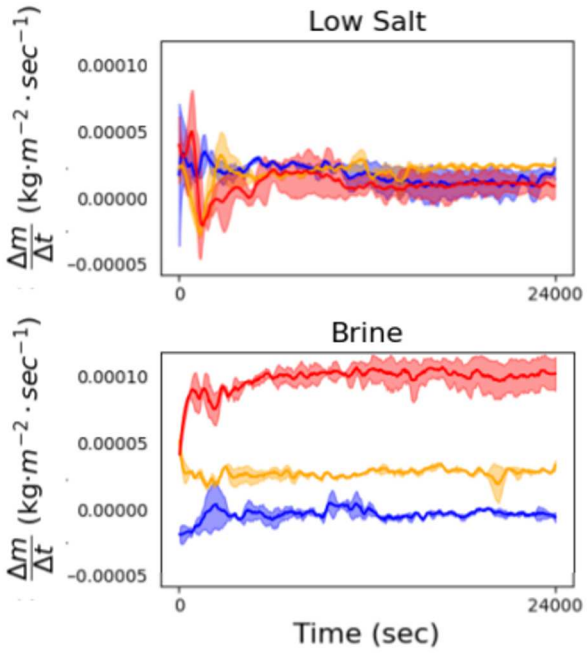

Figure 2. Mass change data showing different salinity concentrations and light intensities. The effect gets stronger as we increase both salinity and light intensity (red line). When the light is decreased, so does the rate of mass change. When the light remains the same, the effect is stronger, just by varying the amount of salinity. Reference data is obtained by performing an identical experiment adjacent to the setup, as shown in Fig.1

3 Results & Discussion

Fig. 2 shows the mass differential data obtained from various sets of experiments. All data shown is an average of three experiments with error-bars shown as a semi-transparent fill. The red lines on the graph show the experiments where the AlN wick is illuminated with full power and the orange lines are 1/3 power. As the salinity increases, the red lines are higher. As we increase the salinity in our brine, the red line increases from $\mu = 2.15 \times 10^{-3}, \sigma = 4.8 \times 10^{-4}$ to $\mu = 2.87 \times 10^{-3}, \sigma = 3.2 \times 10^{-4}$, or about a 1/3 increase in effect. When the light is turned off, salinity plays a minimal role in the evaporation rates, as evidenced by the relatively flat blue lines in each graph. Typically, this increase in the evaporation could be attributed to a thermal effect, however we identify trends with different illumination wavelengths that indicates evaporation is accelerated at 405-nm wavelengths compared to infrared wavelengths. Additionally, the unchanged salinity of the reservoir indicate a different mechanism associated with light.

4 Conclusion

In conclusion, we have built an experimental setup to resolve the effect of light on sensitive evaporation and capillary processes. In the presence of 405-nm light on an AlN wick, the evaporation rate increases because the bandgap energy of AlN closely matches the binding energy of salt-water bonds. Our work has implications for understanding charge transfer in novel systems and water separation processes, including outdoor evaporative cooling operations.

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