An integrated microcombustor and photonic crystal emitter for thermophotovoltaics

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An integrated microcombustor and photonic crystal emitter for thermophotovoltaics

Walker R. Chan¹, Veronika Stelmakh¹,², William R. Allmon³, Christopher M. Waits³, Marin Soljacic⁴, John D. Joannopoulos¹,⁴ and Ivan Celanovic¹

¹ Institute for Soldier Nanotechnologies, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA
² Department of Electrical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, Massachusetts 02139, USA
³ Sensors and Electron Devices Directorate, US Army Research Laboratory, 2800 Powder Mill Rd., Adelphi, Maryland 20783, USA
⁴ Department of Physics, Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, Massachusetts 02139, USA

E-mail: wrchan@mit.edu

Abstract. Thermophotovoltaic (TPV) energy conversion is appealing for portable millimeter-scale generators because of its simplicity, but it relies on a high temperatures. The performance and reliability of the high-temperature components, a microcombustor and a photonic crystal emitter, has proven challenging because they are subjected to 1000–1200°C and stresses arising from thermal expansion mismatches. In this paper, we adopt the industrial process of diffusion brazing to fabricate an integrated microcombustor and photonic crystal by bonding stacked metal layers. Diffusion brazing is simpler and faster than previous approaches of silicon MEMS and welded metal, and the end result is more robust.

Power demand for mobile electronics and robotics continues to rise but current Li-ion battery chemistry is approaching its thermodynamic limit [1]. Thermophotovoltaic (TPV) energy conversion is promising as a high specific energy, millimeter-scale portable power source capable of harnessing the energy content of hydrocarbon fuels (12.6 kWh/kg compared to 180 Wh/kg for batteries) without moving parts or working fluids. In TPV, a microcombustor heats a photonic crystal emitter to incandescence and the resulting spectrally confined thermal radiation drives low-bandgap photovoltaic (PV) cells to generate electricity, as shown in Fig. 1(a). The microcombustor reacts propane and oxygen in a catalyst-loaded serpentine channel to heat the photonic crystal to 1000–1200°C. The microstructured tantalum 2D photonic crystal is engineered to only emit thermal radiation that is convertible by the PV cell, leading to high efficiency [2–4]. In this paper, we report a simple and stable method for fabricating an integrated microcombustor and photonic crystal (hot side assembly) by diffusion brazing.

Designing a stable TPV hot side has been challenging because of the high temperatures and the thermo-mechanical stresses arising from thermal expansion mismatch between the microcombustor and photonic crystal. Microcombustors (for TPV and other applications) have been fabricated from silicon by MEMS techniques [5–7], from laminated metal layers by diffusion bonding [8], and from welded metal components [9, 10]. These methods are difficult
and unreliable. In the past, to integrate the photonic crystal, we directly deposited a multilayer silicon/silicon dioxide stack (1D photonic crystal) onto a MEMS microcombustor [7], or welded a 2D tantalum photonic crystal to an Inconel microcombustor [11]. The optical performance offered by the multilayer stack and the thermal contact offered by welding were not ideal. Diffusion brazing can be used to both fabricate the microcombustor and integrate the tantalum photonic crystal without any of these limitations.

Diffusion brazing is an industrial process similar to brazing, however addition and subsequent diffusion of melting point depressants out of the brazing alloy increases its remelt temperature—allowing the assembly to be reliably operated above the original brazing temperature. In this work, we chose BNi-2 (Lucas-Milhaupt) for the brazing alloy, with a solidus temperature of 971°C and a liquidus temperature of 999°C, and the following composition: 7% chromium, 3% boron, 4.5% silicon, 3.0% iron, and balance nickel. The braze alloy is subjected to a prolonged anneal above its liquidus, during which the silicon and boron diffuse out and the molten alloy undergoes isothermal solidification [12–14]. Assuming the silicon and boron are completely removed, the remelt temperature exceeds 1400°C [15]. The increase in remelt temperature enables us to use the same braze alloy for multiple brazing steps, to avoid exposing the photonic crystal to a higher temperature than absolutely required, and to perform the brazing in a low-cost furnace which was limited to 1200°C even through the target operating temperature is 1000–1200°C.

We were concerned that significant stresses, and therefore deflections, could occur in the final brazed assembly owing to the differential thermal expansion between Inconel and tantalum. Inconel was required for the microcombustor for its high-temperature oxidation resistance, low cost, and machinability; tantalum was required for the photonic crystal for its low vapor pressure, low optical loss, and etchability. We modeled the deflection of an Inconel-tantalum bimetallic strip in SolidWorks Simulation using available material properties and found significant deflection. To test the validity of the simulation, two test coupons with 1.02 mm and 3.18 mm thick Inconel and 0.51 mm thick tantalum were prepared, and deflections of 1.1 and 0.2 mm were measured, 2–3 times greater than simulated values possibly because of inconsistent material properties or plastic deformation. To prevent deflection, we balanced the stress with a symmetric design and eliminated long spans by brazing each channel wall to both the top and bottom Inconel caps, as shown in Fig. 1(b).

The microcombustor channels were designed as described in Ref. 9 and fabricated by abrasive water jet cutting from Inconel sheet stock. The holes for the tubes were reamed over-sized to ensure a consistent 25 µm gap between the tube and hole so that the braze would reliably flow by capillary action. Tubing was commercially available and was simply cut to length. We
bent a loop in the center tube to relieve stress arising from differing thermal expansion between inlet and outlet tubes, visible in Fig. 2(a). The photonic crystal was fabricated separately, as described in Ref. 4. Braze preforms were fabricated from foil by photochemical machining using dry film photoresist and ferric chloride etching solution commonly used for printed circuit board fabrication. Preforms were dimensioned to deliver a slight excess of braze alloy to the joint.

Brazing was conducted in three steps: tubes were brazed to the channels, caps were brazed to seal the channels, and the photonic crystals were brazed to the completed microcombustor. Jigs were used to hold components in place for each of the steps. The jigs used for the first and second brazing operations were machined from Inconel. The one for the final brazing operation was machined from tantalum to avoid contamination of the photonic crystal, as some outgasing of the Inconel was observed.

Brazing was performed a quartz tube furnace evacuated by a turbomolecular pump. We relied on the high temperature and high vacuum to shift the chemical equilibrium to favor the dissociation of surface oxides before the braze alloy melted [12–14]. Flux and reactive atmospheres (e.g. hydrogen) were avoided to prevent contamination of the photonic crystal. After pump-down, the furnace was ramped at 10°C/minute, with one hour stops at 350°C and 500°C for degassing, to a final brazing temperature of 1100°C. When the brazing temperature was reached, furnace pressure would initially spike to $5 \times 10^{-5}$ Torr then reduce to $3 \times 10^{-6}$ Torr. The temperature was held at 1100°C for two hours to ensure full diffusion before returning to room temperature.

During process development, we fabricated ten hot side assemblies with bare tantalum substituted for the photonic crystal, and experienced high fabrication yield as defined by visual inspection and helium leak detection. A cross section of one is shown in Fig. 2(b) and (c). One microcombustor without a photonic crystal was operated for one week without failure or visual damage. Once we had perfected the brazing process, we used a photonic crystal instead of bare tantalum. The finished assembly is shown in Fig. 2(a). Reflectance measurements of the photonic crystal before and after brazing confirmed no degradation of optical properties of the photonic crystal.

In summary, we adopted the industrial process of diffusion brazing and fabricated an integrated Inconel microcombustor and tantalum photonic crystal to serve as the hot side of a millimeter-scale TPV generator. In diffusion brazing, fast-diffusing elements contained in the alloy diffuse out of the joint during heating, thus increasing the remelt temperature of the braze above the original brazing temperature. Table 1 compares this method to prior methods of silicon MEMS and welded Inconel. This approach represents a breakthrough for TPV because it integrates the microcombustor and photonic crystal, and is fast, simple, and reliable. Diffusion
brazed Inconel is applicable to microcombustor fabrication for other applications, and to other millimeter-scale devices operating at high temperatures.

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**References**

[1] Zu C X and Li H 2011 *Energy & Environmental Science* 4 2614
[2] Celanovic I, Jovanovic N and Kassakian J 2008 *Applied Physics Letters* 92 193101
[3] Yeng Y X, Ghebrebrhan M, Bermel P, Chan W R, Joannopoulos J D, Soljacic M and Celanovic I 2012 *Proceedings of the National Academy of Sciences* 109 2280–2285
[4] Stelmakh V, Rinnerbauer V, Geil R D, Aimone P R, Senkevich J J, Joannopoulos J D, Soljačić M and Celanovic I 2013 *Applied Physics Letters* 103 0–4
[5] Peck J, Jacobson S A and Waitz I A 2010 *Journal of Engineering for Gas Turbines and Power* 133 1–10
[6] Marton C H, Haldeman G S and Jensen K F 2011 *Industrial & Engineering Chemistry Research* 50 8468–8475
[7] Chan W R, Bermel P, Pilawa-Podgurski R C N, Marton C H, Jensen K F, Senkevich J J, Joannopoulos J D, Soljačić M and Celanovic I 2013 *Proceedings of the National Academy of Sciences of the United States of America* 110 5309–14
[8] Matson D W, Martin P M, Stewart D C, Tonkovich A, White M, Zilka J and Roberts G 1999 3rd *International Conference on Microreaction Technology* 3rd International Conference on Microreaction Technology
[9] Chan W R, Willhite B A, Senkevich J J, Soljačić M, Joannopoulos J and Celanovic I 2013 *Journal of Physics: Conference Series* vol 476 p 12017
[10] Tolmachoff E D, Allmon W and Waits C M 2014 *Applied Energy* 128 111–118
[11] Chan W R, Stelmakh V, Waits C M, Soljačić M, Joannopoulos J D and Celanovic I 2015 *Journal of Physics: Conference Series* vol 660 p 012069
[12] Pattee H E 1980 *Sourcebook on Brazing and Brazing Technology* ed Schwartz M M (Metals Park, OH: American Society for Metals) pp 17–63
[13] Schwartz M M 1989 *Sourcebook on Brazing and Brazing Technology* ed Schwartz M M (Metals Park, OH: American Society for Metals) pp 109–132
[14] Schwartz M 2003 *Brazing* (Materials Park, OH: American Society for Metals)
[15] Villars P 1995 *Handbook of ternary alloy phase diagrams* (Materials Park, OH: ASM International)