Integrated near-field thermo-photovoltaics for heat recycling

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Energy transferred via thermal radiation between two surfaces separated by nanometer distances can be much larger than the blackbody limit. However, realizing a scalable platform that utilizes this near-field energy exchange mechanism to generate electricity remains a challenge. Here, we present a fully integrated, reconfigurable and scalable platform operating in the near-field regime that performs controlled heat extraction and energy recycling. Our platform relies on an integrated nano-electromechanical system that enables precise positioning of a thermal emitter within nanometer distances from a room-temperature germanium photodetector to form a thermo-photovoltaic cell. We demonstrate over an order of magnitude enhancement of power generation ($P_{\text{gen}} \sim 1.25 \mu \text{Wcm}^{-2}$) in our thermo-photovoltaic cell by actively tuning the gap between a hot-emitter ($T_E \sim 880$ K) and the cold photodetector ($T_D \sim 300$ K) from ~500 nm down to ~100 nm. Our nano-electromechanical system consumes negligible tuning power ($P_{\text{gen}}/P_{\text{NEMS}} \sim 10^4$) and relies on scalable silicon-based process technologies.
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arvesting of thermal energy can be performed using radiation from systems with hot surfaces by placing a cold photodetector at nanometer distances. At nanometer (near-field) distances, strong heat exchange occurs due to evanescent modes, thermal radiation that cannot propagate from the hot body towards the far-field, but can evanescently couple from a hot to a cold surface when the separation is sub-wavelength\(^1\). Near-field radiative heat exchange have been demonstrated to overcome the blackbody limit at small gaps \(d\) between the hot and cold surfaces and scales as \(1/d^\alpha\) (\(1 \leq \alpha \leq 2\); \(\alpha\) is a geometry-dependent factor). Potential applications of this effect include electricity generation on-demand from heat exchangers and thermal management systems in industrial and space applications\(^{11-13}\).

Realizing a scalable platform that utilizes near-field heat transfer to generate electricity remains a challenge due to difficulty of fabricating two large-area surfaces separated by a small gap, while also simultaneously maintaining a large temperature differential between the surfaces as required for energy harvesting\(^{21-29}\). The gap between the surfaces needs to be small enough to induce near-field enhancement while preventing surface contact under the effects of intrinsic film stresses, thermal stresses, surface forces (Casimir forces, Van der Waals forces, etc.) and fabrication process variations\(^{30,31}\). While the underlying theory of heat exchange via near-field radiation has been widely studied over the past decade, it has only been recently demonstrated for energy generation using a lab-scale table-top experiment based on precision nano-positioning systems\(^32\), or platforms relying on intermediate material spacers that limit the possible near-field enhancement\(^33\).

**Results**

We demonstrate a scalable near-field thermo-photovoltaic that allows us to control the heat flux through precise tuning of the distance between a hot suspended metallic thermal emitter and a room-temperature photodetector. The scalable platform is shown in Fig. 1a while the electron microscope image of an individual thermo-photovoltaic (TPV) cell is shown in Fig. 1b. The TPV cell consists of a suspended emitter, underlying photodetector and a pair of actuators for mechanical control. The suspended thermal emitter \((80 \times 15 \mu m^2)\) consists of a metallic thin-film supported by a layer of amorphous silicon (a-Si) and anchored to silicon dioxide \((SiO_2)\) pads with the help of multiple flexures (pad area: \(A_{pad} \approx 450 \times 450 \mu m^2\), \(t_{SiO_2} \approx 300 \text{ nm}\)). The suspended emitter overlaps the actuation electrode at each end \((A_{overlap} = 5 \times 15 \mu m^2)\) while the rest of the bridge area overlaps the active region of a photodetector. The in-plane photodetector and the actuation electrode are separated by a distance of 4 \(\mu m\). The suspended emitter is brought closer to the underlying photodetector by virtue of electrostatic attraction through the application of an actuation potential \(V_{act}\) to the actuators. The multiple flexures holding the central bridge of the emitter provide the required spring-like restoring force for controlled tuning of the gap. The details of the device dimensions are provided in Supplementary Note 1, and the fabrication procedure is provided in the “Methods” section.

We choose a tungsten-chrome thin-film thermal emitter and a germanium photodetector to demonstrate electricity generation from near-field radiative heat transfer. Fig. 2a-inset shows the cross-section of our TPV cell with various films stacks that constitute the emitter and the photodetector. We choose tungsten (W) as thermal emitter due to its thermal stability at high temperatures and compatibility with silicon processing technology. Thin-film chromium is required to achieve adhesion and nucleation of W films to the silicon bridge on the top and to the underlying sacrificial layer during the fabrication process. Our choice of Ge photodetector is due to its relatively lower bandgap \((E_g \approx 0.67 \text{ eV})\) that theoretically allows us over 16% spectral overlap (amounting to ~62.5 mW cm\(^{-2}\)) with our emitter at \(T_E = 900 \text{ K}\) as compared to a silicon \((E_g \approx 1.1 \text{ eV})\). The Ge surface is covered with a thin-film of alumina \((t_{Al_2O_3} = 10 \text{ nm})\) to avoid electrical shorting and damage to its active region. Plot of Fig. 2a shows the spectral heat flux from the metal emitter \((Cr-W-Cr, t_{Cr} \approx 80 \text{ nm}, t_{Cr} \approx 5 \text{ nm})\) as absorbed by a room-temperature Ge photodetector \((t_{Ge} \approx 2 \mu m)\) placed 500 nm, 100 nm, and 50 nm apart computed using a fluctuational electrodynamics model (FED)\(^{34-38}\). The power absorbed by the photodetector increases significantly when the emitter and photodetector are separated by sub-wavelength distance. At larger gaps (far-field), the radiative power absorbed by the photodetector is much smaller due to the limited thermal energy carried out by only the propagating modes. At sub-wavelength distances (near-field) the increase in absorbed power is due to evanescent coupling of thermal radiation from the hot-emitter to the cold photodetector. The details of the simulation model and the dispersion plots \((\omega - k)\) for the far-field and near-field are provided in Supplementary Note 2. The computation results shown here are made at emitter temperature of 900 K and photodetector temperature of 293 K.

Our TPV design relies on thin-film metallic emitter with high-thermal resistance to achieve effective thermal insulation between the hot-emitter and the underlying photodetector, allowing heat transfer only through radiation. Figure 2b shows the heat map of the structure when the emitter is heated to high temperatures. One can see that while the emitter temperature is over 900 K, the temperature of the photodetector embedded in the substrate remains at 300 K. Maintaining such a large temperature difference between the emitter and the photodetector is essential for energy harvesting purposes. According to the Carnot efficiency limit \(\eta_{\text{Carnot}} = (T_H - T_C)/T_H\) where, \(T_H\) and \(T_C\) are temperatures of hot and cold surfaces, respectively, the efficiency of a heat engine increases with a larger temperature difference between hot and cold sides. Furthermore, higher temperature differential also results in higher power density at the photodetector. The thermal circuit of the structure is provided in Supplementary Note 6. The heat map shown in Fig. 2b is computed using a finite element heat transfer model considering a full substrate thickness \((t_{sub} \approx 750 \mu m)\) with its back surface held at constant temperature \((T_{\text{back}} = 293 \text{ K})\). Effects of detector heating due to absorption of near-field heat exchange are appropriately taken into account (see Supplementary Note 6).

We show electrostatic control of gap, from 500 nm to 100 nm, between a suspended metallic emitter and the underlying Ge photodetector. We extract the displacement of the emitter surface by using the known initial gap \((d_0)\) and measured change in capacitance caused by displacement of the bridge due to applied actuation potential \((V_a)\). We confirm that the bridge is suspended and obtain the initial gap \((d_0 \approx 500 \text{ nm})\) by performing an atomic force microscopy (AFM) measurement between the suspended bridge and the photodetector surface (see Supplementary Note 4). The measured initial gap is found to be more than the thickness of deposited sacrificial layer \((t_{\text{SiO}_2} \approx 300 \text{ nm})\) due to bowing of the bridge under film-stress. The change in capacitance between the suspended bridge and the gate electrode as a function of actuation (emitter-gate) potential \((V_a)\) is measured using a vector network analyzer\(^{39-41}\). The details of measurement setup are provided in the Supplementary Note 7. Using the initial capacitance \((C_0 = C_{actuated}/d_0)\), where \(C_0 = 8.85 \times 10^{-12} \text{ F m}^{-1}\) and measured change in capacitance for different gate-emitter potential, the displacement of the suspended bridge-emitter is estimated. Figure 3 shows the gap between the emitter and the photodetector.
silicon (a-Si) anchored on two silicon dioxide (SiO2) pads. The zoomed in schematic shows a single unit cell, where one can see the suspended bridge, the partially underlying actuation electrode and the photodetector region. The silicon substrate over which the cell is fabricated is not shown here. The central (The measurements shown here are performed under vacuum to overcome the limitation of low breakdown voltage of air (Vb~0.4 V) at extremely small distances (d ≤ d0) in our devices.

We show an 11x (±2x) increase in generated electrical power as the distance between the suspended hot-emitter and the underlying detector is reduced from ~500 nm to ~100 nm. We heat the thin-film emitter to high temperatures by passing electrical current (P \text{in} ≈ 58 mW). The temperature is estimated based on the independently measured coefficient of resistance (\(\alpha \approx 1.6 \times 10^{-4} \text{K}^{-1}\)) and real-time estimation of the initial resistance \(R_0\). Details of temperature estimation are provided in Supplementary Note 7. During the process of heating the suspended emitter we ensure that the parasitic thermal conduction into the detector is negligible (\(\Delta T_\text{D} \approx 17 \text{ K}\)), by estimating the change in detector temperature using its IV characteristics\(^{45,46}\). Calculations for estimating the detector temperature are provided in Supplementary Note 5. We apply a NEMS actuation potential (V_a) while maintaining the emitter temperature and simultaneously measure the IV characteristics of the detector. Figure 4a shows the measured IV characteristics of the Ge detector for 0 ≤ V_a ≤ 1.5. As expected, the IV characteristics shift into the power generation quadrant (4th) with an increase in actuation potential as a result of reduction in emitter-detector distance and increase in tunneling of thermal photons\(^{47}\). In order to ensure that the measured change is indeed due to collected photons, we perform independent experiments and measure negligible contribution of electrical leakage paths such as actuator-to-detector, emitter-to-detector and NEMS leakage current. The raw-data for these measurements are provided in Supplementary Note 7 and 8. Moreover, the measurements shown here are limited to V_a = 1.5 V as beyond this bias-point our suspended structures undergo...
unrecoverable damage due to excessive bending. The measurements shown in Fig. 4a are done under vacuum conditions (chamber pressure < 8 × 10^{-5} Torr) to minimize any convective heat losses. Inside the vacuum chamber, the chip rests on a large metallic chuck maintained at room-temperature. The schematic of the measurement setup is provided in "Methods" section.

We generate ∼1.25 μW cm⁻² from the near-field radiation between the hot Cr-W-Cr emitter at T_E = 880 K ± 50 K and the Ge photodetector at T_D = 301 K ± 9 K. Figure 4b shows the generated power by our photodetector as a function of its distance from the suspended emitter. The collected power by Ge photodetector increases significantly (11 x ± 2 x) as the gap reduces from ∼500 to ∼100 nm. The generated power (P_gen) is given by the area of the largest rectangle that fits under each IV curve—P_gen = V_oc × I_sc × (n - 1); V_oc and I_sc are the open-circuit voltage and short-circuit current estimated from the IV characteristics of Fig. 4a, respectively, while FF is the fill factor (FF ∼ 0.25)⁴⁸. Note that the power generated is much larger than the driving power for the capacitive NEMS structure shown here (P_gen/P_NEMS = 10¹); where P_NEMS = 0.5 × C_NEMS × V_a², C_NEMS is the gate-emitter capacitance). The experimental data is seen to closely follow the theoretical prediction for the enhancement in heat transfer at small distances computed using FED. The computational data shown here takes into account the responsivity of our Ge photodetector and the bending of the emitter bridge under the influence of actuator bias V_a. The computation details are provided in Supplementary Note 2. The response of the NEMS at higher voltages (V_a > 1 V) is extracted using the non-linear fit described earlier. The error-bars reported in generated power are computed based on multiple measurements of detector I_sc while the error-bars reported in the gap-estimation are computed from the capacitance measured over a frequency band.

Discussion

The overall efficiency of the TPV is governed primarily by the spectral mismatch between the emitter and the photodetector along with the photodetector quantum efficiency. In our experiments, the spectral overlap at emitter temperature of 880 K, is ∼14% of the total emitted spectrum, equivalent to 49 mW cm⁻² (see Supplementary Note 2). The overall spectral mismatch however, improves at higher emitter temperatures as more thermal radiation is concentrated above the detector bandgap, making it more suitable for high-temperature energy harvesting. Moreover, surface roughness of the emitter and detector is also known to modify the spectral overlap⁴⁹,⁵⁰. In our case the measured root-mean-squared roughness of the emitter and detector surface is found to be σ_Emitter ~ 1.7 nm and, σ_Det ~ 1.1 nm respectively. Our theoretical calculations suggest that the spectral overlap takes an extra ~8% penalty due to the surface roughness (see Supplementary Note 3). The thickness of detector-layer (Ge) also plays an important role in total power absorbed with ~12% reduction for a 10% reduction in thickness. The performance of our TPV cells is also limited by the low efficiency (η_TPV ≈ 0.3 × 10⁻¹⁴ %) of Ge photodetector arising from high recombination in the doped Ge regions (see Supplementary Note 9) possibly arising from dislocation defects at the epitaxial growth interface⁵¹.

Our reconfigurable TPV platform, demonstrated using standard silicon fabrication process technology, can be scaled for harnessing waste heat by proper engineering of heat channels from source to emitter⁵². Considering the current state-of-art germanium photovoltaic detectors with quantum efficiency of over 10%, we can significantly improve the overall efficiency of our TPV (>4 mW cm⁻²)⁵³. Leveraging the NEMS technology also allows us to overcome fabrication limitations by making TPV cells with larger initial gaps between emitter and detector, which

Fig. 2 Computational analysis of near-field heat transfer in our thermophotovoltaic cell. a Calculated spectral heat flux of thermal radiation absorbed by room-temperature germanium when the hot-emitter (aSi-Cr-W-Cr) is placed at near-field distances (50 nm, blue-line, 100 nm, green line) and, far-away (500 nm, red-line). Inset shows: schematic of the material stack of emitter and photodetector of the thermo-photovoltaic cell. In the hot-stack, chromium (Cr) film helps in adhesion and nucleation of tungsten thin-film, while a-Si provides mechanical support when the bridge is suspended. The cold-stack is composed of Ge-on-silicon and covered with 10 nm alumina (Al₂O₃) to protect the surface and avoid any unwanted current leakage from bridge to photodetector in case of shorting during measurement. The temperature of the emitter is assumed to be 900 K.

b Simulated temperature distribution in the structure when the emitter is heated up to high temperatures. The insets show the cross-section of the structure at different positions. One can see that the when the emitter is hot (shown by red) the clamped edges at the pad and the substrate remain at room-temperature (shown in blue), due to high-thermal resistance of the thin-film emitter.

Fig. 3 Nano-electromechanical switch characterization. Displacement of suspended emitter as a function of applied gate-emitter potential difference (V_a). The broken line represents fit to a non-linear spring model (see Supplementary Note 7), while the scatter points show the experimental data.
can then be brought closer electrostatically with minimal operating power. A reconfigurable NEMS platform will also offer on-demand heat recycling and temperature control for systems with constant temperature fluctuations. Reconfigurable NEMS-based TPV platforms can find applications in dynamic heat recovery and cooling systems employed in data centers, as well as metal foundries.

**Methods**

**Fabrication process.** Ge photodetector cell fabrication: germanium photodetector is fabricated on a silicon handle wafer. The epitaxial Germanium (Ge) layer ($t_{Ge} = 1.8 \, \mu m$) is grown using GeH4 on a standard 8" silicon wafer in a reduced pressure-chemical vapor deposition chamber. A low-temperature/high-tempreature strategy is used, together with some short duration thermal cycling, to form a protective layer for W-emitters. The bridges are then suspended by a release step where the bridge is suspended. The a-Si layer acts as a protective layer for W-films while Al2O3 helps protect the Ge surface during the release step.

**Measurement procedure.** The measurements are performed inside a vacuum chamber using dedicated source meters (Keithley 2400) for applying heating power to the emitters, measurement of detector characteristics (IVs), and applying NEMS gate bias. The circuit connections are shown below in Fig. 5. The heating power is gradually applied to the heaters while simultaneously measuring the change in resistance of the heaters, change in diode temperature and any electrical leakage between emitter and NEMS gate. Once the desired temperature is achieved (i.e., temperature at which detector current is high enough to continue the NEMS measurements), the NEMS gate potential is applied and diode IV characteristics are recorded. The source meter used for measuring the diode IV characteristics is set to averaging 25 data samples with an integration time of ~80 ms per sample. The Fig. 5 (inset) shows the equivalent circuit of the TPV device along with external source meter connections.
Data availability
The data that support the findings of this study are available within the article and the Supplementary Information file.

Code availability
Simulation codes are open-access available, details can be found in the Supplementary Information file reference list. Details of data-analysis and fitting methods are provided in the Supplementary Information file.

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References
1. Polder, D. & Van Hove, M. Theory of radiative heat transfer between closely spaced bodies. Phys. Rev. B 4, 3303–3314 (1971).
2. Shchegev, A. V., Joulain, K., Carminati, R. & Greffet, J.-J. Near-field spectral effects due to electromagnetic surface excitations. Phys. Rev. Lett. 85, 1566–1569 (2000).
3. Mulet, J.-P., Joulain, K., Carminati, R. & Greffet, J.-J. Enhanced radiative heat transfer at nanometric distances. Micros. Nano. Thermoph. Eng. 6, 209–222 (2002).
4. Narayanaswamy, A., Shen, S. & Chen, G. Near-field radiative heat transfer between a sphere and a substrate. Phys. Rev. B 78, 115303 (2008).
5. Hu, L., Narayanaswamy, A., Chen, X. & Chen, G. Near-field thermal radiation between two closely spaced glass plates exceeding Planck’s blackbody radiation law. Appl. Phys. Lett. 92, 131301 (2008).
6. Basu, S., Zhang, Z. M. & Fu, C. J. Review of near-field radiative heat transfer between macroscopic planar surfaces. Phys. Rev. Lett. 107, 104301 (2011).
7. Song, B., Fiorino, A., Meyhofer, E. & Reddy, P. Near-field radiative thermal transport: from theory to experiment. AIP Adv. 5, 053503 (2015).
8. St-Gelais, R. et al. Hot carrier-based near-field radiative heat transfer. Nat. Nanotechnol. 11, 515–519 (2016).
9. Reboud, V. et al. Germanium based photonic components toward a full micro/nanophotonic systems. Nat. Nanotechnol. 51, 9 (2018).
10. Sze, S. M. & Kwok, K. N. Semiconductor Devices (Wiley-Interscience, 2012).

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Author contributions
R.S., G.B., S.F., and M.L. conceived the design of the TPV. G.B. and R.S. designed the TPV cell. B.Z. and G.B. performed the heat transfer simulations and theoretical analysis. G.B. performed the NEMS simulations, device design, and fabrication flow and optimization. J.H. provided the epitaxial germanium on silicon. G.B. and S.R. performed the fabrication of TPV cells. G.B. performed the TPV measurements, device characterization, and data analysis. G.B. and I.D. performed the VNA measurements for NEMS characterization. I.D., T.L., and A.M. provided critical feedback at different stages of device design, experiments and data analysis. G.B. and M.L. prepared the manuscript. S.F., B.Z., R.S., A.M., S.R. edited and provided feedback on the manuscript.

Competing interests
The authors declare no competing interests.

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