

# Ultra-Efficient Thermally Undercut Silicon Photonic Devices in a 300 mm CMOS Foundry Process

**Robert Parsons<sup>1</sup>, Kaylx Jang<sup>1</sup>, Yuyang Wang<sup>1</sup>, Asher Novick<sup>1</sup>, A. Matthew Smith<sup>2</sup>, Christopher C. Tison<sup>2</sup>, Yonas Gebregiorgis<sup>3</sup>, Venkatesh Deenadayalan<sup>3</sup>, Matthew van Niekerk<sup>3</sup>, Lewis Carpenter<sup>4</sup>, Tat Ngai<sup>4</sup>, Gerald Leake<sup>4</sup>, Daniel Coleman<sup>4</sup>, Xiang Meng<sup>1</sup>, Stefan Preble<sup>3</sup>, Michael L. Fanto<sup>2</sup>, Keren Bergman<sup>1</sup>, and Anthony Rizzo<sup>2,5,\*</sup>**

<sup>1</sup>Department of Electrical Engineering, Columbia University, New York, NY 10027, USA

<sup>2</sup>Air Force Research Laboratory Information Directorate, Rome, NY 13441, USA

<sup>3</sup>Electrical and Microelectronic Engineering, Rochester Institute of Technology, Rochester, NY 14623, USA

<sup>4</sup>American Institute for Manufacturing Integrated Photonics (AIM Photonics), Albany, NY 12203, USA

<sup>5</sup>Thayer School of Engineering, Dartmouth College, Hanover, NH 03755, USA

\*[anthony.j.rizzo@dartmouth.edu](mailto:anthony.j.rizzo@dartmouth.edu)

## ABSTRACT

Silicon photonic devices fundamental to high-density wavelength-division multiplexed (DWDM) optical links and photonic switching networks, such as resonant modulators and Mach-Zehnder interferometers (MZIs), are highly sensitive to fabrication variations and operational temperature swings. However, thermal tuning to compensate for fabrication and operational temperature variations can result in prohibitive power consumption, challenging the scalability of energy-efficient photonic integrated circuits (PICs). In this work, we develop and demonstrate a wafer-scale thermal undercut in a 300 mm complementary metal oxide semiconductor (CMOS) foundry that dramatically improves the thermal isolation of thermo-optic devices by selectively removing substrate material beneath the waveguides and resonators. This approach significantly reduces the power required for thermal tuning across multiple device architectures, achieving almost a 5× improvement in tuning efficiency in a state-of-the-art 4.5 μm radius microdisk modulator and a 40× improvement in efficiency for a MZI phase shifter. Additionally, to the best of the authors' knowledge, we demonstrate the first wafer-scale analysis of the impact of undercut trench geometry on device performance using comprehensive wafer-scale measurements across 64 reticles of a 300 mm silicon-on-insulator (SOI) wafer. These results highlight the effectiveness of this wafer-scale thermal undercut technique in minimizing energy consumption, paving the way for scalable, ultra low-power silicon photonic systems.

## Introduction

Silicon photonic devices, such as resonant modulators, resonant filters, and Mach-Zehnder interferometers (MZIs), are foundational elements in dense wavelength-division multiplexed (DWDM) optical links and photonic switching systems due to their compact size, high-speed operation, and low energy consumption<sup>1–10</sup>. These devices leverage silicon's strong thermo-optic effect for efficient tuning and configurability, making them highly attractive for large-scale photonic integrated circuits (PICs) in data centers and high-performance computing (HPC) environments<sup>11</sup>. Static fabrication variations and dynamic temperature variations can significantly shift the optical properties of these devices, necessitating the use of integrated micro-heaters to stabilize and tune their performance<sup>12</sup>. As silicon photonics scales towards dense integration with electronic components in co-packaged optical interconnects, the demand for precise thermal tuning increases. While some resonant modulators with high electro-optic tuning abilities<sup>13,14</sup> have been proposed to reduce the reliance on thermal tuning, their tuning range is below what is required for realistic temperature swings in co-packaged interconnects. Trimming the refractive index of devices post-fabrication has also been proposed<sup>15</sup>, which compensates for fabrication variations, but does not solve the challenge of large temperature swings within the package. Therefore, thermal tuning of these devices is still required. However, conventional thermal tuning approaches, which require constant heating to counter localized temperature swings, impose a high power consumption burden. For instance, micro-heaters in resonant modulators can consume up to 25 mW P<sub>π</sub>, which is unsustainable for energy-efficient DWDM links and switching networks, where minimizing energy per bit is a critical requirement<sup>16–18</sup>. Reducing the energy consumption of these thermal tuning elements is essential for enabling scalable, low-power photonic systems<sup>19,20</sup>.

In this work, we address the challenge of thermal management and energy reduction by introducing a selective thermal substrate undercut technique across a range of key silicon photonic devices, including microdisk modulators, microring &

racetrack modulators, and linear thermo-optic phase shifters in MZIs. These devices, widely used for modulation, wavelength multiplexing, and switching, all rely on thermal tuning for stable operation<sup>21</sup>. By selectively removing the substrate material beneath the waveguides and resonators, the thermal undercut creates a region of enhanced thermal isolation, which significantly reduces the power required for thermo-optic tuning. This approach improves thermal efficiency while maintaining the performance and compactness of the devices. Previous demonstrations of thermal undercut show ample improvements in thermo-optic tuning efficiency, however these demonstrations have the disadvantages of requiring backside etching<sup>22</sup>, low-volume electron-beam lithography<sup>23,24</sup>, or not achieving full release from the substrate<sup>25</sup>. Recent foundry-supported thermal undercut demonstrations yield moderate improvement factors, limited by the sealing of the undercut<sup>26,27</sup>. Substrate undercut has also been applied to other contexts, including enabling integrated photonic MEMS<sup>28</sup>.

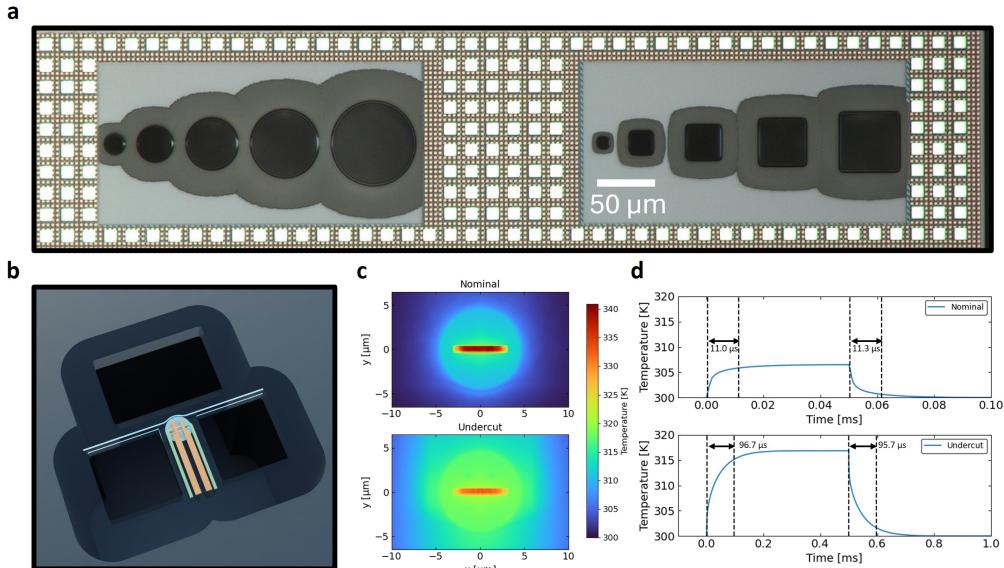
Resonant modulators, which are crucial for high-speed modulation in DWDM systems due to their inherent wavelength selectivity, benefit from reduced tuning power with the thermal undercut technique. We apply the wafer-scale thermal undercut to microring modulators, racetrack-style ring modulators, and state-of-the-art vertical junction microdisk modulators. Our experimental results demonstrate significant gains in tuning efficiency, achieving almost a  $5\times$  improvement for the microdisk modulators, while maintaining CMOS-compatible drive voltages. Linear thermo-optic phase shifters in MZIs, crucial for interleaving, switching, and routing in photonic networks, exhibit even greater reductions in power consumption, with over  $40\times$  improvement in tuning efficiency with optimized trench geometries. Furthermore, we demonstrate the capability of arbitrarily defined undercut openings, providing room for future improvement in all designs with optimized opening geometry.

To the best of the authors' knowledge we present, for the first time, wafer-scale measurements of undercut microdisk modulators, illustrating tuning efficiency trends based on systematically varied undercut geometric parameters. By sweeping the dimensions and shapes of the undercut openings beneath these microdisk modulators, we observe that wider and more elongated trenches yield significantly improved thermal isolation and reduced power consumption. These measurements reveal the critical role of trench geometry in optimizing thermal performance, providing key insights for design strategies that maximize tuning efficiency across photonic systems. The reduction in power consumption achieved through this optimized undercut geometry has broad implications for DWDM links and other high-density photonic systems. In DWDM links, where minimizing power per channel is essential for scalability<sup>29</sup>, the improved thermal efficiency allows for higher channel counts and lower energy-per-bit metrics, critical for data center and telecom applications. Similarly, in efficient large-scale photonic switching systems<sup>30</sup>, the power savings gained through thermal undercut can alleviate the thermal load, enabling increased switching density with minimized power consumption. These findings establish wafer-scale thermal undercut as indispensable to advancing energy-efficient silicon photonics, addressing key challenges in power reduction for next-generation silicon photonic systems.

## Results

We design and demonstrate robust wafer-scale thermal undercut in collaboration with a 300 mm CMOS foundry<sup>31</sup>, ensuring that the process can extend to high-volume manufacturing. As shown in Fig. 1a, design of experiment test structures with both circular and square trench geometries validate the ability to process a range of arbitrary shapes in a standard CMOS fabrication process. This flexibility is essential for optimizing thermal isolation across different device architectures and confirms the robustness of the undercut technique for varied applications. Comprehensive design rules ensure devices retain structural integrity when surrounded by undercut trenches. The thermal undercut process employed in this work involves selectively removing silicon substrate material<sup>32</sup>. This creates an air-filled trench that significantly enhances thermal isolation by lowering the effective thermal conductivity surrounding the active photonic device. Silicon, with a thermal conductivity of approximately 150 W/m·K<sup>33,34</sup>, provides a highly conductive pathway for heat dissipation, causing significant thermal leakage from the micro-heater to the bulk substrate. Further, the buried oxide has a thermal conductivity of approximately 1.4 W/m·K<sup>35,36</sup>, representing reduced thermal confinement. By introducing an undercut trench filled with air, which has a thermal conductivity of roughly 0.025 W/m·K<sup>37</sup>, we reduce both heat dissipation pathways, effectively creating an insulating barrier around the device. This drastic reduction in thermal conductivity between the heater and the substrate allows the device to reach higher temperatures with lower input electrical power, significantly improving thermal tuning efficiency.

Thermal simulations<sup>38</sup> were performed on a microdisk modulator both with and without undercut to compare their transient thermal responses<sup>39</sup>. A schematic representation of a microdisk modulator surrounded by thermal undercut is shown in Fig. 2b. The comprehensive device design is detailed in ref.<sup>40</sup>, and preliminary results of the undercut device are shown in ref.<sup>41</sup>. Simulations in which 1 mW of power was applied through the integrated micro-heater show a significantly higher temperature increase in the undercut microdisk compared to the nominal device, underscoring the enhanced thermal isolation achieved by the trench (Fig. 2c). This heightened temperature response for the same input power demonstrates the potential for lower power consumption, as less energy is required to reach the desired tuning temperatures in devices with thermal undercut. Additionally, transient thermal simulations were performed to provide insight into the dynamic response of the undercut device, revealing longer rise and fall times compared to the nominal device. Specifically, the nominal device had a rise time of 11.0  $\mu$ s and a fall

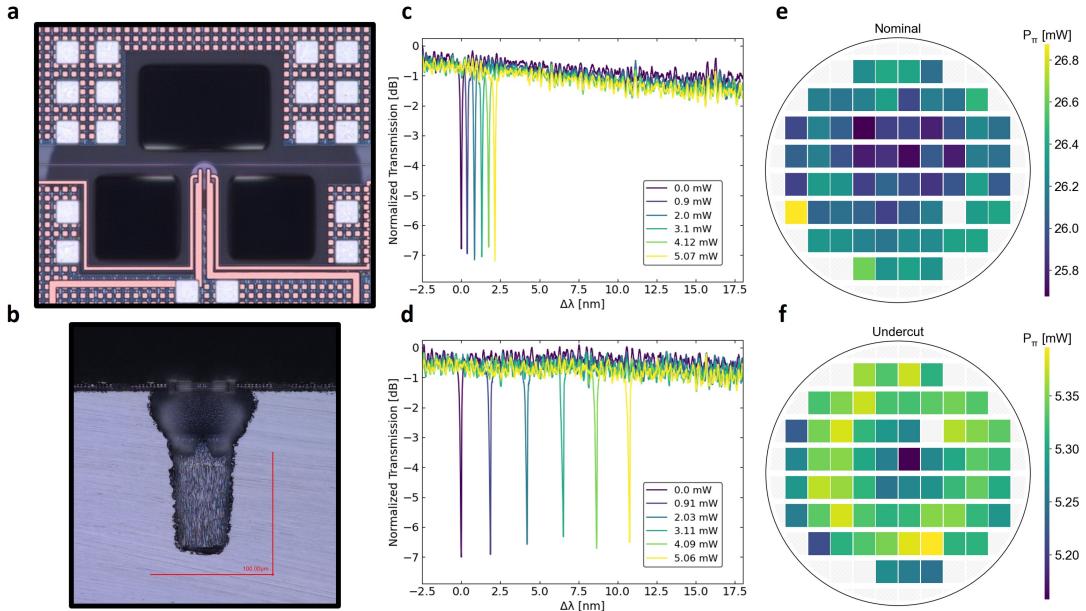


**Figure 1. Thermal undercut design-of-experiment structures and thermal simulation results.** **a**, Design-of-experiment circular and square undercut structures, verifying that the undercut etch can extend to arbitrary geometries. **b**, Three dimensional schematic render of microdisk modulator with thermal undercut, showing the undercut openings and the lateral extent of the substrate removal beyond these openings. **c**, Simulated temperature distribution of nominal (top) and undercut (bottom) microdisk modulator with 1 mW applied power to the integrated microheater. **d**, Simulated thermal transient of nominal (top) and undercut (bottom) microdisk modulator, with time constants of approximately 11  $\mu$ s for the nominal device and 96  $\mu$ s for the undercut device.

time of 11.3  $\mu$ s, while introducing the undercut resulted in a rise time of 96.7  $\mu$ s and a fall time of 95.7  $\mu$ s. The approximately 8-9 $\times$  slower heating and cooling transients are a result of the reduced thermal conductivity around the microdisk due to the air gap created by the undercut. This effect can be advantageous in applications where slower thermal responses improve stability by reducing sensitivity to temperature fluctuations.

Microdisk modulator test structures were measured across two 300 mm wafers. Two variants of the device were measured on each reticle: modulators both with and without thermal undercut. A micrograph of a microdisk modulator with thermal undercut is shown in Fig. 2a, which confirms that the device is fully released from the substrate. Further demonstrating the full release of the device, a micrograph of the side profile is shown in Fig. 2b. A dicing saw was used to make a precise cut close to the undercut modulator on a singulated die to enable capture of the cross-section. The optical spectrum of a nominal microdisk modulator without thermal undercut at different applied thermo-optic phase shifter powers showing the shift in resonance is displayed in Fig. 2c. A drastic increase in the resonance shift for similar applied powers is shown in Fig. 2d, where the optical spectrum of a representative thermally undercut microdisk modulator is displayed. This large increase in tuning efficiency is additionally observed at the wafer-scale; the wafer maps are shown in Fig. 2g-h, showing the  $P_\pi$  of the nominal non-undercut and undercut microdisks, respectively. The  $P_\pi$  for the undercut microdisks is on average 5.32 mW, which is an improvement of 4.92 as compared to the  $P_\pi$  of 26.14 mW exhibited by the devices without undercut. Furthermore, these wafer-scale measurements confirm the structural integrity and high yield of the undercut devices.

To demonstrate the wide applicability of the undercut process, two other types of resonant modulators were fabricated, both with and without thermal undercut. The first device is a lateral junction microring modulator with a radius of 20  $\mu$ m. The micrograph of this microring modulator with thermal undercut is shown in Fig. 3a. The thermo-optic phase shifter is located concentrically inside the ring. Trench openings were placed both inside and outside the microring and alongside the access waveguide. The second device is a racetrack-style ring modulator; a micrograph of a representative device is shown in Fig. 3d. A linear thermo-optic phase shifter is located internal to the ring along the straight access section. The PN-junction for high-speed modulation is located along the opposite straight section. For this modulator design, trench openings were placed both internally and externally along the straight sections of the ring and alongside the access waveguide. The  $P_\pi$  measured across a wafer is shown for the non-undercut microring modulator and racetrack ring modulator in Fig. 3b and Fig. 3e, respectively. The  $P_\pi$  wafer maps of the undercut microring and racetrack modulators are displayed in Fig. 3c. and Fig. 3f, respectively. We see an average tuning efficiency improvement of 25.1, from 100.01 mW without undercut to 3.98 mW with undercut for the microring modulator. In the case of the racetrack-style ring modulator, the tuning efficiency improvement on

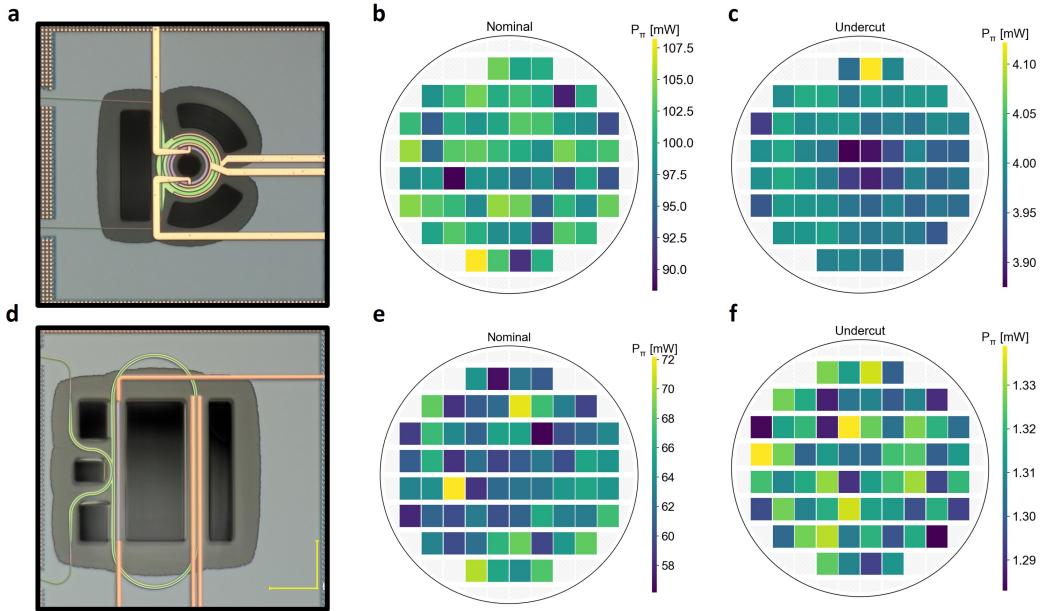


**Figure 2. Undercut microdisk modulator wafer-scale thermo-optic measurements.** **a**, Micrograph of undercut microdisk modulator showing that the device is fully released. **b**, Cross-section micrograph of undercut microdisk modulator after dicing through test structure. **c**, Transmission spectrum of nominal microdisk modulator. **d**, Transmission spectrum of undercut microdisk modulator. **e**, Wafer map of tuning power of nominal microdisk modulator. **f**, Wafer map of tuning power of undercut microdisk modulator.

average is 48.1, from 63.11 mW without undercut to 1.31 mW with undercut. Both undercut devices exhibit drastic increases in tuning efficiency, indicating full release from the substrate.

While all the fully-released undercut resonant devices show substantial improvements in tuning efficiency, the improvement factor is more pronounced for less efficient thermo-optic phase shifter designs. The baseline tuning efficiencies of the microring and racetrack modulators without undercut have  $P_\pi$  values of 100.01 mW and 63.11 mW, respectively. In comparison, the already relatively efficient microdisk modulator exhibits a  $P_\pi$  of 26.14 mW without undercut. The higher baseline efficiency of the microdisk can be attributed to its integrated thermo-optic phase shifter, which is surrounded by only a thin 100 nm oxide layer for electrical isolation<sup>42</sup>. The proximity of the phase shifter to the optical mode, with silicon as the dominant material between them, ensures effective thermal conduction due to silicon's higher thermal conductivity compared to oxide. In contrast, the thermo-optic phase shifters in the microring and racetrack modulators are positioned farther from the optical mode, separated by a larger oxide gap. This separation significantly reduces thermal efficiency and confinement in these devices compared to the microdisk. As a result, the microring and racetrack modulators benefit more, relatively speaking, from the enhanced thermal isolation provided by the substrate undercut, achieving greater improvement factors in tuning efficiency.

In addition to resonant devices, we designed and fabricated linear thermo-optic phase shifters both with and without undercut. A micrograph of the phase shifter with undercut is shown in Fig. 4a. The phase shifter consists of two doped silicon strips parallel to the waveguide. To extract the tuning efficiency of the phase shifter, it was placed within an imbalanced MZI so the interference fringes could be tracked at varying heater powers. The transmission spectrum of the MZI without undercut and with undercut under different applied heater powers is shown in Fig. 4c and Fig. 4d, respectively. The undercut phase shifter requires significantly less power to induce a larger shift in interference fringe wavelength. This is demonstrated in the wafer maps showing  $P_\pi$  for the phase shifters without undercut and phase shifters with undercut in Fig. 4g and Fig. 4h, respectively. An improvement factor of 40.5 is shown, moving from a non-undercut  $P_\pi$  of 43.46 mW to a  $P_\pi$  of 1.07 mW for the undercut device. To characterize the time-dependent transient effects of substrate undercut on thermal modulation, we apply a square wave to the phase shifter. The transient is shown for the phase shifter without undercut in Fig. 4e, and similarly Fig. 4f shows the transient for the phase shifter with undercut. A pulse width of 100 μs was applied to the non-undercut device, resulting in a rise time of 12.6 μs and a fall time of 25.3 μs. For the undercut device, a pulse width of 10 ms was used, resulting in a rise time of 1.853 ms and a fall time of 1.258 ms. The increase in rise/fall time has implications on the performance of these phase shifters in the context of optical switches and multiplexers. For instance, the increase in rise/fall time results in a slower optical switching speed. However, the reduced switching speed disadvantage is mostly negated if the network topology is configured



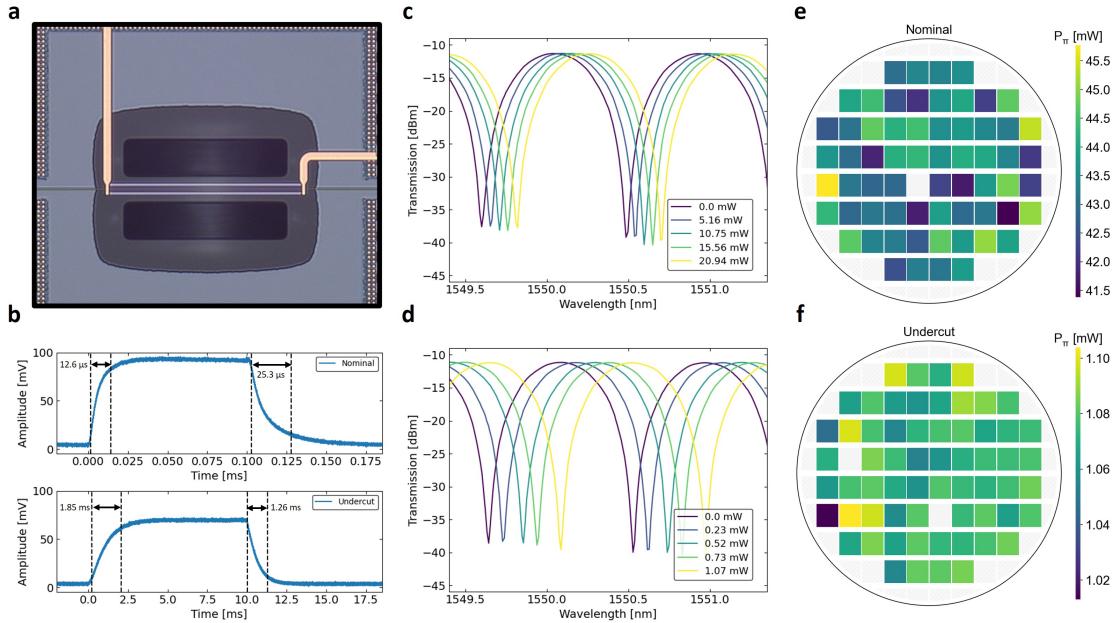
**Figure 3. Undercut microring and racetrack modulator wafer-scale thermo-optic measurements.** **a**, Micrograph of undercut microring modulator. **b**, Wafer map of tuning power of nominal microring modulator. **c**, Wafer map of tuning power of undercut microring modulator. **d**, Micrograph of undercut racetrack modulator. **e**, Wafer map of tuning power of nominal racetrack modulator. **f**, Wafer map of tuning power of undercut racetrack modulator.

before application runtime<sup>43,44</sup>. Further, the increase in rise/fall time can be leveraged when considering time-multiplexed driving signals for many thermo-optic phase shifters to reduce electrical I/O<sup>45</sup>.

To elucidate the impact of undercut geometry on the tuning efficiency of devices, we swept the undercut geometric parameters across a number of resonant devices. A micrograph of the test structure sweep of undercut microdisk modulators is shown in Fig. 5a. While keeping the microdisk modulator design constant for all cases, both the undercut opening size and separation were varied according to the schematic in Fig. 5b. The tuning efficiency of each microdisk modulator in the undercut parameter sweep was extracted across two full wafers. The tuning efficiency of each modulator in the parameter sweep, averaged across the first wafer, is shown in Figs. 5c and 5d, where the top trench length is 20 and 40  $\mu\text{m}$ , respectively. Similarly, the tuning efficiencies of the modulators from the second full wafer are shown in Figs. 5e and 5f. First, there is a clear trend in increased tuning efficiency (reduced  $P_\pi$ ) in all cases as the trench width is increased from 10  $\mu\text{m}$  to 25  $\mu\text{m}$ . The larger trench opening increases the lateral undercut, ensuring the devices are fully released from the substrate. However, we see diminishing returns when increasing the trench width from 20  $\mu\text{m}$  to 25  $\mu\text{m}$ , suggesting the tuning efficiency of the devices is dominated by the volume of remaining buried oxide and substrate contacting the bottom of the device. Additionally, there is a trend in increased  $P_\pi$  when the trench separation is increased, which corresponds to wider oxide bridges between the trench openings. This trend explains the limited gains in tuning efficiency seen in processes using a sealed substrate undercut<sup>26,27,46</sup>; heat from the phase shifter is less confined to the device without the trench openings. Another notable trend is the marked consistency in tuning efficiency of the undercut modulators between both wafers, demonstrating the robustness and reliability of the substrate removal process.

The small size of microdisk modulators causes strong light confinement, leading to high optical power density and nonlinear effects like thermal bistability<sup>47</sup>. Thermal isolation exacerbates this by trapping heat in the microdisk, complicating high-power management in resonant modulators. We studied the effects of high optical power in thermally undercut microdisk modulators, and thermal instability even at -14 dBm input power is observed<sup>48</sup>. The modulator is thermally isolated using wafer-scale undercut, shown in Fig. 6a. We examined electro-optic modulation of the PN-junction at varying laser powers. At low input laser power (-17.5 dBm), the DC spectral response showed a modulation efficiency of 95 pm/V under bias voltages from 0.5 V to -2.5 V (Fig. 6b). However, increasing laser power caused nonlinear spectral shifts with resonance red-shifting and broadening due to thermal instability, as shown in Fig. 6c. Near-resonance laser light is partially absorbed via two-photon and free-carrier absorption, generating heat. This effect is enhanced by the thermal isolation of the undercut structure, leading to significant thermal instability at laser optical powers as low as -14 dBm (Fig. 6d).

Despite this, robust high-speed modulation was achievable over a broad spectral range at higher powers, up to -4 dBm.



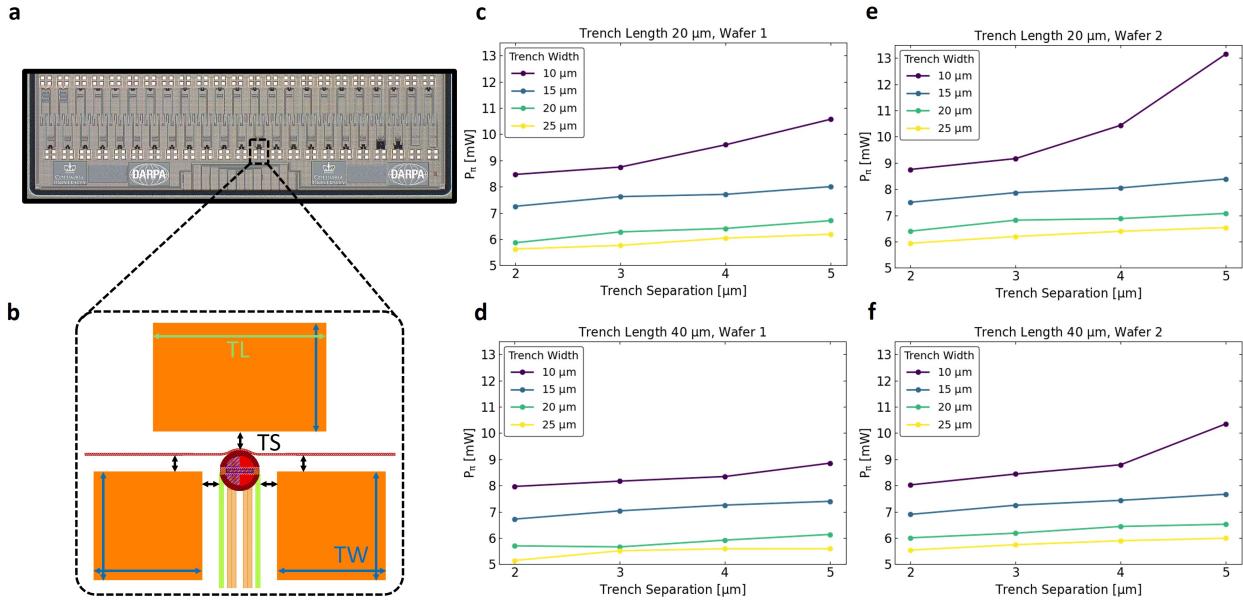
**Figure 4. Undercut linear thermo-optic phase shifter wafer-scale measurements.** **a**, Micrograph of undercut linear thermo-optic phase shifter. **b**, Transient response of nominal (top) and undercut (bottom) thermo-optic phase shifter. **c**, Transmission spectrum of nominal thermo-optic phase shifter. **d**, Transmission spectrum of undercut thermo-optic phase shifter. **e**, Wafer map of tuning power of nominal thermo-optic phase shifter. **f**, Wafer map of tuning power of undercut thermo-optic phase shifter.

Thermally-induced resonance red-shifting enabled modulation over a range  $6\times$  wider than the resonator's passive linewidth. We present an experimental investigation of optical modulation in thermally undercut microdisk modulators, focusing on the advantages of optically induced thermal nonlinearity. As laser power increases, the spectral shift of the resonator becomes nonlinear, accompanied by a redshift and resonance broadening due to thermal instability. We also explored the modulation behavior across varying operating frequencies and input optical powers. A 2 V peak-to-peak square wave was applied at different frequencies, and the peak-to-peak optical modulation was measured and normalized to compare modulation depths. Across all modulation frequencies, the spectral range broadens with increased laser power. However, at low frequencies ( $<1$  MHz, Fig. 6e), although the spectral range expands, the peak-to-peak modulation decreases at higher laser powers, likely due to the device's thermal response. In contrast, at higher data frequencies ( $>25$  MHz, Fig. 6f-h), the modulation depth remains stable as laser power increases, achieving modulation over a spectral range six times broader than the resonator's linewidth at an optical power of -4 dBm. Therefore, at high data rates, the device's thermal sensitivity becomes a beneficial nonlinear effect, enabling robust modulation across a wide spectral range. Thermal isolation thus enhances modulation efficiency and reduces micro-heater tuning requirements.

## Discussion

In conclusion, we demonstrate a wafer-scale thermal undercut in a 300 mm CMOS foundry applied to a range of fundamental silicon photonic devices with state-of-the-art performance and yield. We show an excellent  $40\times$  improvement in tuning efficiency of linear thermo-optic phase shifters with undercut, enabling a drastic reduction in power consumption of large-scale silicon photonic circuits. Undercut microring and racetrack-style modulators also exhibit high tuning efficiency, owing to their ability to accommodate both larger and elongated external trench openings along with an internal trench opening. Further, we apply the developed undercut etch to state-of-the-art microdisk modulators, achieving an almost  $5\times$  improvement in tuning efficiency. These efficiently tunable compact vertical-junction microdisk modulators with high modulation efficiency are fully compatible with CMOS driving voltages, enabling scalable, ultra efficient DWDM links.

By systematically varying the undercut trench geometry and measuring tuning efficiencies across multiple full wafers of microdisk modulators, we identified key trends that reveal how trench dimensions impact thermal tuning efficiency. Wider and more elongated trenches consistently provide improved thermal isolation, resulting in significant reductions in the power required for thermal tuning. Further, reduced trench separation also resulted in higher tuning efficiency. This finding suggests that trench geometry optimization can serve as a powerful design parameter for further minimizing power consumption in



**Figure 5. Influence of undercut geometry on device thermo-optic performance.** **a**, Optical microscope image of the undercut microdisk modulator test structures with parameter sweeps of opening geometry. **b**, Schematic layout of the microdisk modulator with undercut openings illustrating the swept design parameters. TS: trench separation; TL: trench length; TW: trench width. **c-f**, Average tuning power required for  $\pi$  phase shift over varying trench width and trench separation with trench length of 10  $\mu\text{m}$  on first wafer (**c**), trench length of 20  $\mu\text{m}$  on first wafer (**d**), trench length of 10  $\mu\text{m}$  on second wafer (**e**), trench length of 20  $\mu\text{m}$  on second wafer (**f**).

future device designs. Notably, through full wafer-scale measurements across 300 mm wafers, we additionally demonstrate the robustness of the thermally undercut devices through the high yield and low  $P_\pi$  standard deviation. By establishing predictable efficiency gains based on trench geometry, we provide a robust framework for integrating thermal undercut as a standardized process across different CMOS fabrication lines, ensuring reproducibility and consistency at the scale required for high-volume production. This level of scalability is critical for enabling low-cost, high-throughput manufacturing of photonic integrated circuits where consistent thermal performance is essential.

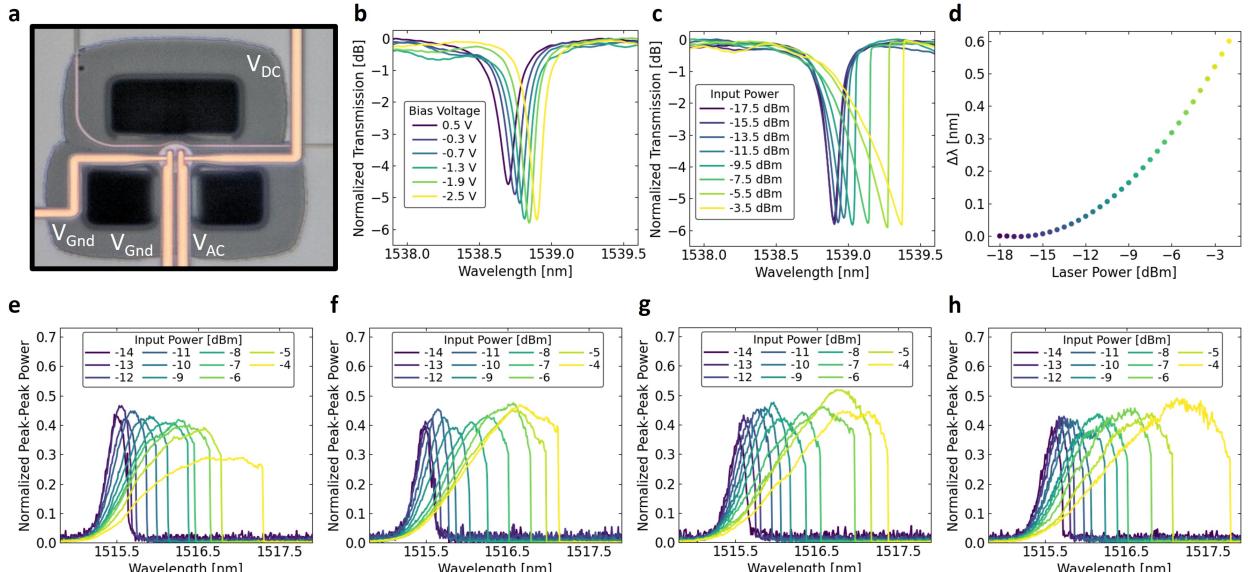
## Methods

### Thermal Undercut Fabrication Process

The thermal undercut fabrication process is run on a 300 mm, CMOS compatible, silicon photonic process<sup>31</sup>. The thermal undercut is run within the back-end-of-line (BEOL) giving it flexibility to be used with photonic, electronic and optoelectronic devices. The undercut can be combined with optical facets and waveguide access via trenches to both silicon and silicon nitride layers. The process consists of two primary steps: 1) silica and 2) silicon etching to ensure efficient and controlled reactive ion etching (RIE) of the different materials. Within each step photolithography is used to define the thermal undercut opening, a ~10  $\mu\text{m}$  photoresist is spun, baked, and exposed using i-line photolithography. Careful optimization of the thermal undercut opening sizes (Fig. 5b TW and TL) and the proximity to the device (Fig. 5b TS) is used to ensure RIE does not damage waveguides or metallization. The RIE etches of both the silica and silicon portion are closely monitored to ensure undercutting of optical facets does not happen and optical facets are produced with smooth straight surfaces.

### Wafer-scale Measurements

All optical measurements were taken using a ficonTEC TL1200 Wafer-Level and Component-Level Tester<sup>49</sup>. The wafer-level tester, with a temperature-controlled chuck, two six-axis stages with optical probes, and two five-axis stages with electrical probes, enables comprehensive wafer-scale measurements. Three dies per reticle, across 64 reticles, were measured to characterize a variety of silicon photonic devices both with and without thermal undercut. The first die contains many grating-coupled microdisk modulators with a sweep of undercut opening geometric parameters. An angled fiber array was coupled to each microdisk modulator with an automated alignment process, and simultaneously multi-contact DC electrical probes were landed to control the integrated thermo-optic phase shifter. A high-precision DC power supply (Keithley 2280S-32-6) was used



**Figure 6. Nonlinear spectral shifts in undercut microdisk modulator.** **a**, Optical microscope image of the undercut resonant device with heater and RF electrical inputs annotated. **b**, Electro-optic depletion response of the device, swept from 0.5 V to -2.5 V at low optical power (-17.5 dBm). **c**, Transmission spectrum of the device with fixed -2.5 V DC bias and increasing laser powers. **d**, Induced spectral shift due to input optical power. **e-h**, Modulation at different input optical powers and modulation frequencies of **(e)** 1 MHz, **(f)** 50 MHz, **(g)** 300 MHz, and **(h)** 600 MHz.

to bias the thermo-optic phase shifter. After tuning the polarization to select for the fundamental transverse-electric (TE) mode with an internal polarization controller (Thorlabs MPC320), a tunable laser source (Keysight 81608A), lightwave measurement system (Keysight 8164B), and optical power meter (Keysight N7744A) were used to sweep the optical spectrum of each device at each phase shifter bias point.

A lidless periscope fiber array was used to edge-couple to the microring modulators, racetrack modulators, and imbalanced Mach Zehnder interferometers (MZIs) on the other two dies on each reticle. The periscope fiber arrays, manufactured by Keystone Photonics, enable wafer-scale low-loss edge-coupling by extending 3D-printed optics into the dicing trench<sup>50</sup>. Following edge-coupling, the optical spectra of each device at different thermo-optic phase shifter bias points were measured using the same methodology as the microdisk modulators. In total, two wafers without thermal undercut were measured, and two wafers with thermal undercut were measured.

The tuning efficiency of each device was calculated by finding the resonance or interference fringe shift at each thermo-optic phase shifter bias point. A peak-finding algorithm was used to find the resonance or fringe wavelength from each optical spectrum sweep. Together with the recorded electrical power dissipated in the thermo-optic phase shifter and the measured free spectral range, the  $P_\pi$ , i.e. the power required for a phase shift of  $\pi$ , was calculated for each device.

The transient responses of the microdisk modulator and imbalanced MZI were measured both with and without thermal undercut. A tunable laser was aligned to the wavelength of the resonance and interference fringe of the microdisk and MZI, respectively. Next, the optical output was switched to a photodiode (Thorlabs PDA10CS), connected to an oscilloscope (Tektronix MSO5204B) set to trigger on the rising edge. An arbitrary function generator (Keithley 3390) was used to send a square wave to the thermo-optic phase shifter, with the resultant transient captured by the oscilloscope. The rise and fall times of each device were extracted by finding the 10% and 90% thresholds of each optical transient.

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## **Author contributions statement**

A.R. and A.N. conceived the device designs, performed initial simulations, and completed the mask layout of the undercut geometry sweeps. V.D. and M.vN. designed and completed the mask layout of the microring, racetrack, and linear thermal phase shifters. L.C., G.L., and D.C. developed the undercut process and fabricated the wafers. C.C.T., A.M.S, and M.L.F. contributed to earlier versions of the undercut design, measurements, and data analysis. Y.G. performed the wide spectral modulation experiments. R.P. led the wafer-scale measurements with assistance from K.J. and the data analysis with assistance from Y.W. and X.M. All authors reviewed the manuscript and contributed to the writing. A.R., K.B., M.L.F, and S.P. supervised the project.

## **Additional information**

### **Competing interests**

The authors declare no competing interests.

### **Data Availability**

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

### **Correspondence**

Correspondence and requests for materials should be addressed to A.R. (email: [anthony.j.rizzo@dartmouth.edu](mailto:anthony.j.rizzo@dartmouth.edu)).