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Thermoreflectance imaging of sub 100 ns pulsed cooling in high-speed thermoelectric microcoolers

Bjorn Vermeersch,1,2,a) Je-Hyeong Bahk,1,2 James Christofferson,3 and Ali Shakouri1,2,b)

1Birck Nanotechnology Center, Purdue University, West Lafayette, Indiana 47907, USA
2Baskin School of Engineering, University of California, Santa Cruz, California 95064, USA
3Microsanj LLC, Santa Clara, California 95051, USA

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Miniaturized thin film thermoelectric coolers have received considerable attention as potential means to locally address hot spots in microprocessors. Given the highly dynamic workload in complex integrated circuits, the need arises for a thorough understanding of the high-speed thermal behavior of microcoolers. Although some prior work on transient Peltier cooling in pulsed operation is available, these studies mostly focus on theoretical modeling and typically deal with relatively large modules with time constants well into the millisecond range. In this paper, we present an extensive experimental characterization of 30 × 30 μm² high-speed coplanar SiGe superlattice microcoolers subjected to 300 ns wide current pulses at ≈300 kHz repetition rate. Using thermoreflectance imaging microscopy, we obtain 2D maps of the transient surface temperature and constituent Peltier and Joule components over the 50–750 ns time range with submicron spatial and 50 ns temporal resolutions. Net cooling of 1 K–1.5 K is achieved within 100–300 ns, well over an order of magnitude faster compared to previous reports on microcoolers in high-speed operation. We also point out ambiguities in separating Peltier and Joule signals during the device turn-off. Overall, our measurements provide substantial insight into ultrafast turn-on and turn-off dynamics in thin film thermoelectrics. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4794166]

I. INTRODUCTION

Thermoelectrics have received continuously growing attention given their potential in power generation, energy conversion, and on-demand cooling applications.1,2 In the context of the latter, miniaturized thin film thermoelectric coolers are of particular significance as an interesting means to address hot spots in microprocessors and optoelectronic devices.3–6 On-demand targeted cooling of localized high heat flux regions could significantly reduce the overall cost and energy consumption of current bulk cooling technologies.4 Given the highly dynamic workload of densely integrated circuits, an increasing need arises for a thorough understanding of the transient behavior of thermoelectric coolers.

A small number of earlier studies on transient pulsed cooling in thermoelectrics are available in the literature.6–14 Particular attention was given to the so called supercooling effects12–14 and cooling performance degradation by parasitic electrical and thermal resistances.4,6,10 The term supercooling expresses the ability to achieve transient active cooling that temporarily exceeds the optimal performance in steady state operation. This phenomenon finds its origin in the fact that Peltier cooling is an interface effect, while its competing Joule counterpart occurs over a bulk region. The smaller thermal mass associated with the former provides a cooling advantage at short time scales in pulsed operation.

The prior work mostly focuses on analytical and numerical modeling of the thermal dynamics, and typically deals with relatively thick modules having response times in the millisecond range and beyond. Limited reported experimental data are comprised of temporal evolutions of single-point or otherwise spatially consolidated measures such as the average cooling over the entire active area.

In this paper, we present an extensive experimental characterization of custom designed high-speed SiGe superlattice microcoolers in the 50–750 ns range by means of CCD-based thermoreflectance imaging. This technique captures detailed 2D maps of the transient temperature field at the sample surface, providing substantial insight into both the thermal turn-on and turn-off characteristics under pulsed current excitation. The remainder of the manuscript first describes the sample layout and experimental procedure, followed by a presentation and discussion of the key results.

II. SAMPLE DESIGN AND FABRICATION

We have fabricated high-speed integrated microcoolers with a thin film (3 μm) Si/Si0.7Ge0.3 superlattice as active thermoelectric medium. The samples contain a variety of active area sizes ranging from 10 × 10 μm² to 50 × 50 μm². The material structure and device layout are illustrated in Fig. 1.

A highly doped SiGe0.1 cap layer is included on top of the superlattice to ensure a good ohmic contact between the supply electrode and superlattice with minimal electric contact resistance. Parasitic Joule heating at the metal/superlattice interface is particularly detrimental to the device

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a)Email: bvermeer@purdue.edu.
b)Email: shakouri@purdue.edu.

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Fig. 1. The material structure and device layout are illustrated in...
performance because the active Peltier cooling is induced at exactly this interface. The wafer additionally contains a SiGe/SiGeC buffer layer between the superlattice and supporting Si substrate to alleviate lattice mismatch strain.

The fabrication procedure consists of first etching down mesa structures into the wafer to define the active areas and ground returns. We then deposit a SiNₓ layer (passivation A in Fig. 1(a)) with openings over the top of the mesas. This ensures that the subsequently deposited electrode is insulated from the underlying substrate and mesa side walls. A second SiNₓ layer passivates the entire sample for environmental protection except for the contact pads (to allow for electrical probing or wire bonding) and active areas (for unconstricted optical access to the cooler surfaces).

To optimize the devices for ultrafast electrical operation, the metallization is laid out as coplanar waveguides (Fig. 1(b)). This transmission line structure consists of a signal carrying electrode symmetrically spaced in between two surrounding ground planes and therefore offers convenient single-sided probing from the top of the sample. More importantly, the characteristic impedance $Z_0$ is almost entirely determined by the geometric ratio of the signal electrode width $w_S$ to that of the signal-to-ground separation gap $w_G$.

III. EXPERIMENTAL METHODS

In Sec. IV, we will present a detailed thermal characterization of the microcoolers by means of transient thermoreflectance imaging. This technique enables to capture 2D temperature maps of integrated electronics with submicron spatial and $\approx 50$ ns temporal resolution without the need for scanning the sample. The main principles of the methodology are illustrated in Fig. 2 and summarized in the following paragraphs. Additional details on thermoreflectance imaging are available elsewhere.

A narrowband LED illuminates the device under test (DUT) through a microscope objective. The resulting image is monitored with a scientific grade CCD camera. As the optical reflectivity of the DUT varies with its surface temperature, a temperature distribution $\Delta T(x, y)$ (relative to ambient) induces a slight but detectable alteration of the amount of reflected light captured by the CCD. The temperature dependence of the reflectivity is roughly linear and can be expressed in terms of the thermoreflectance coefficient $C_{TR}$ (K$^{-1}$). This material and illumination wavelength dependent parameter embodies the relative change in reflectivity $\Delta R/R$ for a one degree temperature variation. The measurements described further are all carried out under green illumination ($\lambda \approx 530$ nm) with associated thermoreflectance coefficient calibrated for the gold electrodes $C_{TR} \approx -2.3 \times 10^{-4}$ K$^{-1}$.

By electrically cycling the DUT between idle and on states and monitoring the relative difference between the according “cold” and “hot” images, we obtain the temperature field at the sample surface

$$\Delta T(x, y) = \frac{R_{\text{hot}}(x, y) - R_{\text{cold}}(x, y)}{C_{TR}(x, y) \cdot R_{\text{cold}}(x, y)}.$$  (1)

Given the typical orders of magnitude for $C_{TR}$, the absolute variations in surface reflectivity are relatively minute. Lock-in techniques and adequate data averaging must be employed to obtain sufficient signal-to-noise ratios. Temperature resolutions down to 10 mK are achievable.

For steady-state characterizations, we supply a sinusoidal bias signal to the DUT with period several orders of magnitude larger than the relevant thermal time constants of the sample. The phase-locked CCD takes 4 images over every cycle under constant illumination from which the magnitude and phase of the slowly oscillating temperature field can be determined.

We have also developed a dedicated method to simultaneously capture Peltier and Joule effects in thermoelectric devices. Based on their respective linear and quadratic current dependences, the signal components can be
separated by locking into the first and second harmonic frequencies of a sinusoidal bias signal with zero offset.

High-speed transients can be imaged by means of pulsed sample excitation under pulsed illumination (Fig. 2(b)). A first pulse train cycles the DUT between on and off states up to several thousand times during a single CCD frame. The duty cycle of the excitation is kept below an appropriate level to avoid excessive steady-state background heating. A second pulse train, phase-locked to the first one with a tunable precise delay, drives the LED to induce short (down to 50 ns) periodic illumination flashes. The CCD, thus, essentially accumulates a sampling of the same point along the thermal transient over and over again during the exposure time. This provides the “hot” frame. In the alternating frames, the LED pulse train is advanced such that the temperature just before the onset of the bias pulse is sampled, providing the “cold” frame. Processing both frames as described earlier in Eq. (1) yields the temperature excursion from the steady-state baseline. By repeating this process at different delay values, we can obtain the thermal transient over the entire period of the excitation signal. Here, too, Peltier and Joule terms can be separated by post-processing two measurement runs at opposite bias current polarity. We will use the convention that forward polarity and positive values for the Peltier term \( D_T \) signify cooling operation, and therefore define

\[
\begin{align*}
\Delta T_P &= \frac{1}{2} (\Delta T_{\text{reverse}} - \Delta T_{\text{forward}}), \\
\Delta T_J &= \frac{1}{2} (\Delta T_{\text{reverse}} + \Delta T_{\text{forward}}).
\end{align*}
\]

\[\text{IV. RESULTS AND DISCUSSION}\]

We first perform quasi-static thermal imaging. This provides a baseline performance characterization and helps validate a correct functionality of the devices. Figure 3 summarizes the obtained cooler temperatures (thermal field averaged over the active area) as function of the amplitude of the 3.75 Hz sinusoidal bias current.

Active net cooling on the order of 2 K to 3 K below ambient is clearly observed. The cooler temperature shows an almost perfectly parabolic trend with respect to the bias current (Fig. 3(a)). This expected behavior can be easily understood in terms of the underlying competing Peltier cooling (Fig. 3(b)) and Joule heating (Fig. 3(c)) effects with respective linear and quadratic current dependence. The optimal bias level \( I_{\text{opt}} \), at which maximum cooling is achieved, scales roughly with the characteristic size of the device, i.e., the square root of the active surface area \( \sqrt{A} \). This indicates that the cooling performance is dominated by 3D thermal spreading effects, which seems very reasonable based on the geometrical layout of the devices (Fig. 1(a)). Indeed, as the mesa etch only reaches half a micron into the upper section of the superlattice, we can expect that the vast majority of the total thermal impedance seen by the Peltier interface source is governed by spreading mechanisms inside the remainder of the superlattice and underlying structures. The fact that the maximum achievable cooling gets smaller with increasing device area (Fig. 3(a)) suggests the presence of parasitic electrode losses and non-ideal interfaces. Our detailed transient imaging results presented further clearly illustrate the degrading impact such parasitics can have on the cooling performance, in particular, for excessive heating in the electrode neck.

The remainder of the paper focuses on the transient characterization of a 30 × 30 \( \mu \text{m}^2 \) cooler. We use pulsed bias excitation with \( \approx 200 \text{ mA} \) magnitude and \( \approx 300 \text{ ns} \) pulse width at 10% duty cycle (Fig. 4).

The LED pulse width, governing the time resolution of the measurement, is set to the smallest attainable value of 50 ns. Figure 5 shows the resulting thermal images over the 50–750 ns time range for both forward and reverse bias current polarity, as well as the associated Peltier and Joule terms inferred through Eq. (2).

These images reveal a lot of information about the high-speed performance of the device, as discussed below.
Additional insight can be gained from thermal cross-section profiles. Pixel data from Fig. 5 are first plotted versus a coordinate along lines parallel with the horizontal device axis, stretching from the wafer, over the active area and electrode neck, into the tapering section. We then calculate a point-by-point average of the resulting graphs over the entire width of the cooler (110 consolidated profiles) to improve the signal-to-noise ratio, producing the results shown in Fig. 6.

Let us focus first on the turn-on characteristics during the bias pulse ($t = 50 - 300 \text{ ns}$, Figs. 5(a)–5(d) and 6(a)–6(d)). As expected, the thermal signals get stronger as time progresses. Net cooling in the active area of up to $1.5 \degree$ within $300 \text{ ns}$ is clearly visible in forward polarity mode (Figs. 5(a) and 6(a)).

Some of our earlier measurements have confirmed that smaller coolers, having smaller thermal time constants, are able to turn on even faster. We have achieved up to one degree of net cooling within $100 \text{ ns}$ in a $10 \times 10 \mu\text{m}^2$ device. These observed response times are well over an order of magnitude faster compared to earlier studies of high-speed operation of thermoelectric microcoolers.

The fact that net cooling can be achieved in transient mode at a current magnitude $I \approx 3.3I_{\text{opt}}$, a level that would lead to destructive overheating in steady state operation, is a manifestation of the supercooling effect mentioned earlier in the Introduction. The fast cooling response is also visualized by the development of notable Peltier activity over the active area (Figs. 5(c) and 6(c)). The overdrive current, however, comes at a cost as it will quadratically exacerbate parasitic electrical losses. In addition to bulk heating of the electrode, the onset of two hot spots near the corners of the active area is highly apparent (Figs. 5(a) and 6(a)). Thermal diffusion from the hot spots into the adjacent electrode metal is also clearly visible. These features can be linked to strong Joule activity at the electrode neck (Figs. 5(d) and 6(d)). We attribute the excessive heating to localized thickness reductions and resulting current constriction. We can indeed expect that the metal deposited along the almost vertical side wall of the mesa may be significantly thinner in comparison with the other almost horizontal electrode sections, even though the sample is slightly tilted in the evaporation chamber to ease this effect (Fig. 7).

Currently, we do not have a full understanding as to why the excessive heating appears predominantly as hot spots near the corners of the active area and not spread out over the entire width of the electrode neck. We believe geometric effects (such as small random irregularities in the $90^\circ$ bend of the overhanging passivation layer) may play a role in the apparent poorer metal deposition in that vicinity.

We note in this context that the electrode design was driven by a compromise between minimizing the thermal mass of the metal (such that it does not hamper experimental detection of ultrafast transitions underneath) while still maintaining good electrical performance. The chosen gold...
thickness value of $\approx 250$ nm provides an estimated subnanosecond thermal diffusion time and measured electrical sheet resistance around 125 m$\Omega$/sq. The fact that the Peltier signal is roughly symmetrical over the cross-section of the active area (Fig. 6(c)) is indicative of a fairly uniform current density over the active area, suggesting the electrical spreading in the bulk of the metal is indeed adequate. We associate the upward edges of the cross-section profiles, i.e., stronger Peltier signal over the edges of the active area, with a combination of two factors. On one hand, optical artifacts may influence the measurement. The variability in thickness and curvature of the sample surface near the cooler edges (as sketched in Fig. 1(a)) will result in non-normal local illumination angles which may influence the thermoreflectance coefficient. Minute system vibrations additionally tend to induce light fluctuations on sharp optical edges such as the mesa side walls. On the other hand, the signals may at least in part reflect an actual physical phenomenon. Even for an ideal cooler free of parasitics with a perfect electrode, the current density will tend to be slightly larger near the edges.
These regions manifest a minor benefit in terms of local input resistance compared to the cooler center, as current in the outer regions will have access to slightly better spreading capabilities when reaching the bottom of the mesa etch.

When the device is operated in reverse current polarity, the Peltier effects no longer compete with the Joule effects but rather worsen them. In the active area, the thermal signal rises to several degrees above ambient over the course of the bias pulse (Figs. 5(b) and 6(b)). The additional device heating also exacerbates the hot spots: the average temperature at the electrode neck increases from about 4.5 K to 7 K (Fig. 6(b)). The difference can be entirely attributed to the reversal of the Peltier component, amounting to 1 K–1.5 K over the neck (Fig. 6(c)), superimposed on a Joule component of roughly 5.5 K (Fig. 6(d)). We also point out that net cooling now becomes visible over the ground electrodes (Fig. 5(b)). Since the ground returns paths are also defined by a mesa etch, their structure is identical to that of the active device area except that the current flows in the opposite direction with respect to the metal/semiconductor interface. In
and 6(e)–6(h)). The thermoreflectance signals gradually disappear as the structure returns to thermal equilibrium with the ambient. One notable exception is the anomalous peak in Peltier activity around 350–400 ns (Figs. 5(g) and 6(g)). Although electrical measurements show a small overshoot of the bias signal in this time range (Fig. 4), the effect can be traced back as a post-processing ambiguity. Strictly speaking, the Peltier/Joule separation in Eq. (2) is only valid in the presence of a bias signal. Indeed, with no external power applied, the difference in thermal behavior between the forward and reverse polarity case is no longer determined by the reversal of one of the constituent physical mechanisms. Rather, both cases are governed by the same diffusion driven return to equilibrium but merely from two different initial conditions. This important distinction is capable of explaining the apparent overshoot in the Peltier signal, as we will see further below. Altogether, the terminology of Peltier and Joule components loses most of its physical meaning during the thermal decay, and strong caution is advisable in interpreting the inferred separated images after the bias pulse.

Using the thermal profiles from Fig. 6, we can investigate the turn-off characteristics for both forward and reverse bias polarities in closer detail for three representative regions of interest: the cooler center, electrode neck, and electrode bulk. Plotting the temperature data versus time on a logarithmic vertical scale results in a set of nearly straight lines in the 350–500 ns range. This indicates that the initial decays are exponential with a single dominant time constant. The inferred values for the time constants are summarized in Table I.

<table>
<thead>
<tr>
<th>Location</th>
<th>Forward bias</th>
<th>Reverse bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooler center</td>
<td>365</td>
<td>843</td>
</tr>
<tr>
<td>Electrode neck</td>
<td>879</td>
<td>1277</td>
</tr>
<tr>
<td>Electrode bulk</td>
<td>432</td>
<td>445</td>
</tr>
</tbody>
</table>

We can obtain a rough theoretical estimation for the thermal time constant of the active area based on a simple diffusion model. The measurements discussed earlier suggest that the response of the active area is mostly determined by the Peltier component and 3D effects. We can, therefore, model the associated transient in first order approximation by thermal spreading from a surface source into 2.5 μm of superlattice. The associated thermal time constant can be estimated as

\[ \tau_{3D} \approx \frac{0.339 d^2}{D} \]  

with \( d \) the length of the flow path (layer thickness) and \( D = k/C_v \) the thermal diffusivity. Having a conductivity \( k = 7.8 \text{ W/m K} \) and stoichiometrically weighted volumetric specific heat \( C_v = 1.64 \text{ MJ/m}^3\text{ K} \), we obtain \( \tau_{3D} = 445 \text{ ns} \). This is in reasonable agreement with the decay constants observed experimentally for the cooler center.

It is interesting to point out that changing from forward to reverse bias polarity significantly increases the decay time for both active area (365 vs. 834 ns) and electrode neck (879 vs. 1277 ns) despite the fact that the initial net thermal gradient between these regions is identical for both cases (−1/4.5 K forward vs. 1.5/7 K reverse at 300 ns). While by no means aiming to grasp the full complexities of the turn-off transients, the temperature decays can be understood quite well by simply considering the energy balance of the electrode metal with respect to the ambient. With \( C_v = 2.49 \text{ MJ/m}^3\text{ K} \) for gold and a 250 nm thickness, we obtain a thermal capacitance of \( \approx 560 \text{ pJ/K} \) for the 30 \( \times 30 \mu\text{m}^2 \) section over the active area. The capacitance of the neck, taken as a 3 μm section, amounts to one tenth (56 pJ/K). Note that we have neglected the suspected thickness reduction in the outer edges of this area. However, the associated capacitance reduction will not alter the qualitative outcome. The observed average temperatures just before turn-off (\( t = 300 \text{ ns} \)) and corresponding estimations of stored thermal energy are summarized in Table II.

<table>
<thead>
<tr>
<th>Region</th>
<th>( \Delta T (K) )</th>
<th>( \Delta E (\text{pJ}) )</th>
<th>( \Delta T (K) )</th>
<th>( \Delta E (\text{pJ}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active area</td>
<td>−1</td>
<td>−560</td>
<td>+1.5</td>
<td>+840</td>
</tr>
<tr>
<td>Electrode neck</td>
<td>+4.5</td>
<td>+252</td>
<td>7</td>
<td>+392</td>
</tr>
</tbody>
</table>

The presence of one of the constituent physical mechanisms. Rather, both cases are governed by the same diffusion driven return to equilibrium but merely from two different initial conditions. This important distinction is capable of explaining the apparent overshoot in the Peltier signal, as we will see further below. Altogether, the terminology of Peltier and Joule components loses most of its physical meaning during the thermal decay, and strong caution is advisable in interpreting the inferred separated images after the bias pulse.
benefits from the incoming heat flux as it will assist the diffusion transient in the superlattice that normally governs the thermal decay. This mechanism accelerates the return to equilibrium for both regions, leading to the smallest decay time constants (Table I). The interaction and “heat sinking” effect is also illustrated in the thermal profiles (Fig. 6(e)), showing that the temperature peak over the neck tends to spread leftwards into the active area.

In reverse polarity, the process turns around. Both active area (840 pJ) and neck (392 pJ) have a significant energy excess. A total net surplus of over 1 nJ must be evacuated through the superlattice mesa (being the path of comparatively least resistance) to return the structure to equilibrium. For the active area, the diffusion driven temperature drop is constantly “topped up” by the incoming heat flux from the neck. In turn, the heat in the latter is prevented from being evacuated swiftly as the overloaded superlattice mesa essentially becomes a bottleneck in the thermal flow path. The described mechanism slows down the decay of both regions, leading to the notable increase in measured time constants compared to forward polarity (Table I).

For regions sufficiently far away from the active area, by contrast, we can expect that the thermal field should not be influenced by the Peltier processes and therefore be independent of the direction of the bias current. The observed time constant for the electrode bulk ($\tau = 40 \mu$m) indeed remains virtually constant under a polarity change (432 ns forward vs. 445 ns reverse). Further inspection shows that the thermal profiles from Figs. 6(a) and 6(b) overlap almost perfectly for $x \geq 20 \mu$m when plotted on the same scale.

Finally, the described energy balance mechanisms can explain the earlier mentioned anomalous overshoot of “Peltier” activity at 350 and 400 ns, well after the end of the bias pulse. With the neck speeding up the decay of the active area in forward polarity and slowing it down in reverse, we have $\Delta T_{\text{forward}} \downarrow$ and $\Delta T_{\text{reverse}} \uparrow$ compared to the turn-off transient based on the diffusive response to the Peltier surface source alone. Inserting this trend into Eq. (2) indeed leads to $\Delta T_{\text{p}} \uparrow \uparrow$.

V. CONCLUSIONS

In summary, we have presented the coplanar design of high-speed SiGe thermoelectric microcoolers and a thorough investigation of their transient characteristics under pulsed current operation in both forward and reverse bias polarities. We use thermoreflectance imaging to obtain highly detailed 2D maps of the transient temperature at the sample surface. Dynamic cooling on the order of 1 K–1.5 K with response times as small as 100 ns is demonstrated. The measurements further enable to assess the current uniformity over the active area and clearly illustrate the performance degrading effect of parasitics such as excessive electrode heating. Finally, we provided a simple qualitative model capable of adequately explaining the thermal decays observed during the device turn-off. Overall, the presented work helps to assess the high-speed performance of thermoelectric devices and provides valuable insight into the physical mechanisms and limitations of Peltier/Joule interactions that govern their transient thermal dynamics.

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