Application of Near-Field thermal Radiation in Thermal Rectifiers

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Backgrounds

Electric technology

Electric Diode

Rectification of electrons flow

Controlling the heat flow may provide alternative ways to process information at harsh conditions.

Thermal Rectification

Thermal Diode

Thermal Rectifier
Heat flow can be realized by three approaches: **Conduction | Convection | Radiation**

**Conduction-based thermal rectifier**

**Convection-based thermal rectifier**
- Avanessian and Hwang, *ICNMM2015* - 48508

**Radiation-based thermal rectifier**

**Merits**: avoid contact and intrusion
Thermal rectification ratio:

\[ R_{\text{ratio}} = \frac{Q_f}{Q_r} - 1 \]
**Flat-plate**

Plate with nanostructures


**Method**

**Nanoparticles-based rectifier** in my work

**Calculating Near-field thermal radiation:**

1. **Two spheres**: spectral poynting vector \( E(r_i, \omega) \times H(r_i, \omega) \)

\[
\begin{align*}
\langle E_{io}(r_i, \omega) H_{jo}^*(r_i, \omega) \rangle &= i \omega \mu_0 \int d^3 r' \left\{ \overline{G_E}(r_i, r, \omega) \overline{G_H}(r_i, r, \omega) \langle J_j(r, \omega) J_m^*(r', \omega) \rangle \right\} \\
\overline{G_E}(r_i, r, \omega) & \quad \text{Dyadic Green’s functions (DGFs)} \\
\overline{G_H}(r_i, r, \omega) & \quad \text{are obtained by using partial-wave}
\end{align*}
\]

2. **Nanoparticles with irregular shapes:**

Thermal discrete dipole approximation method (TDDA):

The emitter and absorber are discretized into electric dipoles with the number of \( N_e \) and \( N_a \)

\[
Q_{es} = \frac{\omega}{2} \sum_{j=N_e+1}^{N_e+N_a} \text{Im} \left[ (\alpha^{-1})^* \right] \left\{ \frac{2}{3} k_0^2 \right\} \text{tr} \left( \overline{R}_{pp} \right)
\]
Electrons of silicon will be excited at high temperatures, which gives rise to the enhancement of radiative heat transfer.

Electrons won’t be excited, which give rise to the constraint of radiative heat transfer.

High rectification ratio

- The temperature-dependent dielectric function of silicon is obtained from Fu and Zhang.

### Results

<table>
<thead>
<tr>
<th>Numbers</th>
<th>Material Pairs</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Intrinsic Si - Doped Si (10^{18} cm^{-3})</td>
<td>6</td>
<td>Doped Si(10^{18} cm^{-3}) - SiO_2</td>
</tr>
<tr>
<td>2</td>
<td>Intrinsic Si - 3C-SiC</td>
<td>7</td>
<td>Doped Si(10^{18} cm^{-3}) - Au</td>
</tr>
<tr>
<td>3</td>
<td>Intrinsic Si - SiO_2</td>
<td>8</td>
<td>3C-SiC - SiO_2</td>
</tr>
<tr>
<td>4</td>
<td>Intrinsic Si - Au</td>
<td>9</td>
<td>3C-SiC - Au</td>
</tr>
<tr>
<td>5</td>
<td>Doped Si(10^{18} cm^{-3}) - 3C-SiC</td>
<td>10</td>
<td>SiO_2 - Au</td>
</tr>
</tbody>
</table>

- Rectification ratios are **all above 100** when intrinsic Si is included in the material pair (See number 1 2 3 4).
- Rectification ratios are less than 5 when intrinsic Si is not included in the material pair (See number 5 6 7 8 9 10).
- A **record-high rectification ratio of more than 10^4** is theoretically achieved when the material pair is intrinsic Si and dope Si (10^{18} cm^{-3}).

Near-field radiative heat flux and rectification ratio of the proposed diode for different material pairs.
In forward biased case, the carrier concentration of intrinsic Si at 1000 K will have nearly the same value as that in doped Si \((10^{18} \text{ cm}^{-3})\) at 300 K. Polarizability of two material will have a strong match.

In the reverse biased case, polarizability for doped Si at 1000 K will merely match the peak induced by absorption of lattice vibration for intrinsic Si at 300 K.
Conclusions

• A highly efficient radiative thermal rectifier consisting of two nanoparticles, i.e., intrinsic Si nanoparticle and a dissimilar nanoparticle, is proposed. Due to the thermal excitation of intrinsic Si at high temperature, rectification ratios can reach more than 100.

• Particularly, for the nanoparticles comprising by intrinsic Si and doped Si \((10^{18} \text{ cm}^{-3})\), the rectification ratio can reach a record-high value of more than \(10^4\) due to the strong match of polarizability.

• Effects of gap distances and configurations of nanoparticles on the rectification ratio can be found in my paper.

Thank you for listening!

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