school of Photovoltaic and Renewable Energy Engineering 光伏与可再生能源工程学院

Laser annealed Ge/Si, a cost-effective virtual Ge substrate for high efficiency III-V multi-junction solar cells

应用于高效率三五族多结太阳能电池的低成本激光退火虚拟锗衬底

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Motivation for III-V solar cells on virtual Ge substrates 目的

- III-V tandem solar cells offers the highest efficiency (World record 46%)
  三五族电池是现今转换效率最高的太阳能电池（世界纪录 46%）
- Ge wafers are commonly used substrates for III-V solar cells
  which accounts for more than 50% of the cell cost
  锗晶片为常用三五族电池衬底，锗晶片占电池总成本50%以上
- Thin epi-Ge on Si wafers can replace Ge wafers with following advantages:
  ✓Si wafer is much cheaper than Ge wafer: lower cost
  ✓Si wafer has superior mechanical properties: lower weight & durable
  ✓Si has higher band-gap than Ge: higher voltage output from bottom cell
  生长在硅晶片上的外延锗薄膜可以用作虚拟锗衬底。相比传统锗晶片，虚拟锗成本低、机械性能好、做为底层电池对总电压及效率贡献更大。

Challenge 挑战

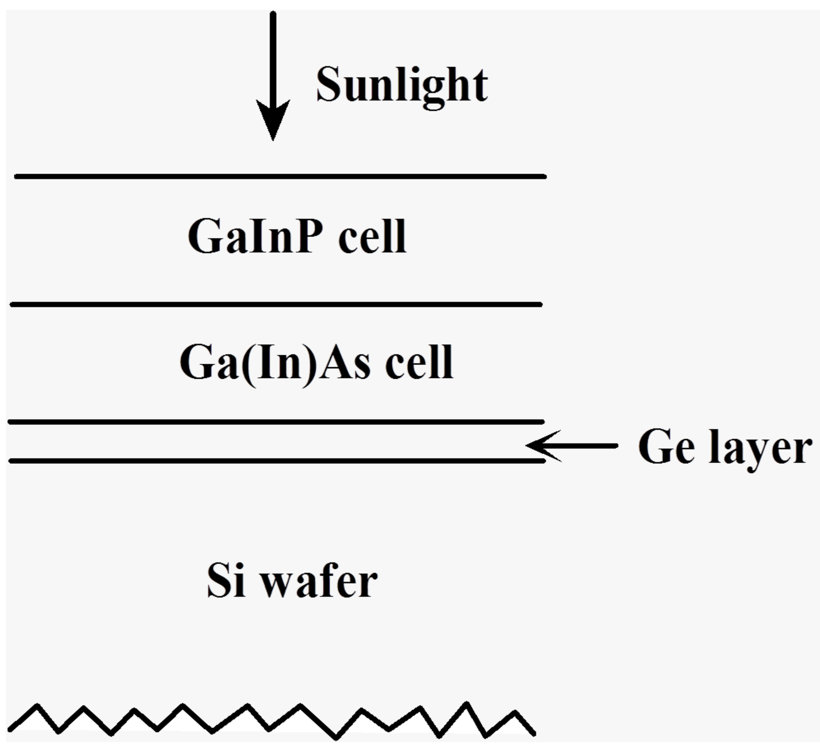
Si & Ge has 4% lattice mismatch: **high threading dislocation density(TDD)**

硅和锗之间4%的晶格失配会导致很高的位错缺陷密度，影响电池效率

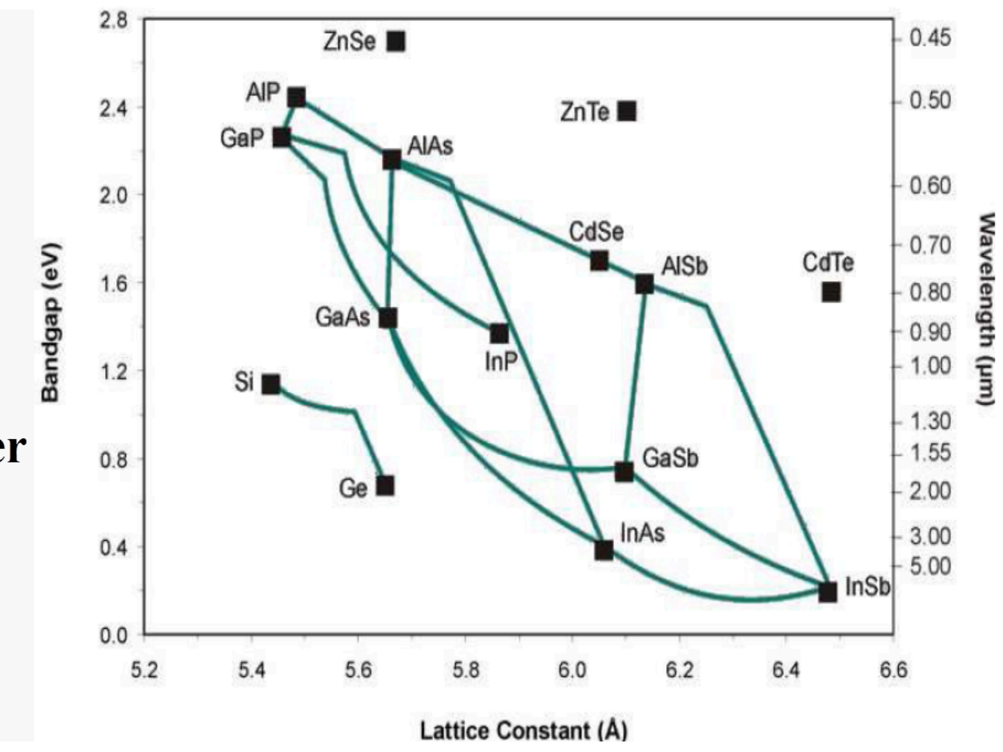
Laser annealing 激光退火

Fast, low-cost, and effective method to reduce defects in Ge thin film

激光退火可以快速、低成本、有效地减少锗薄膜缺陷密度



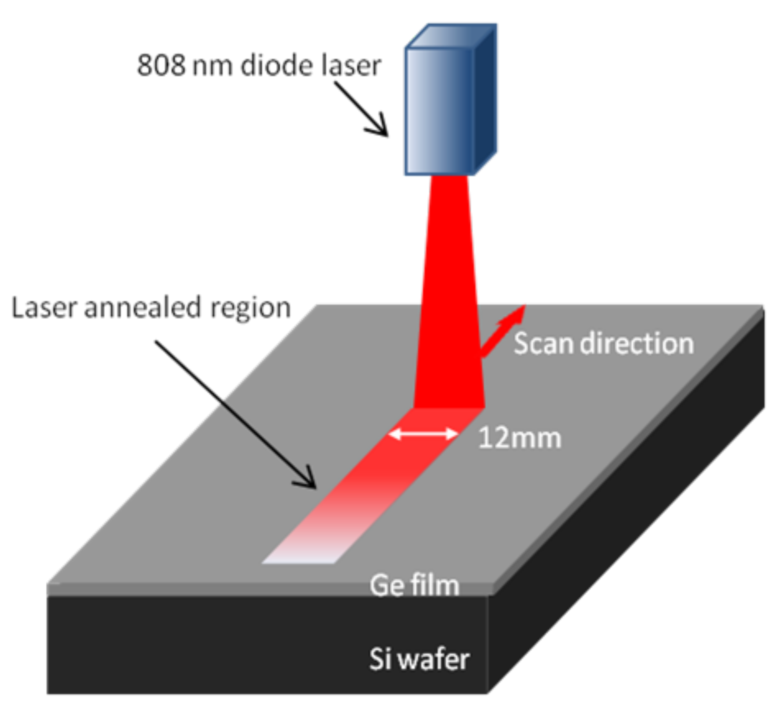
基于虚拟锗的电池结构



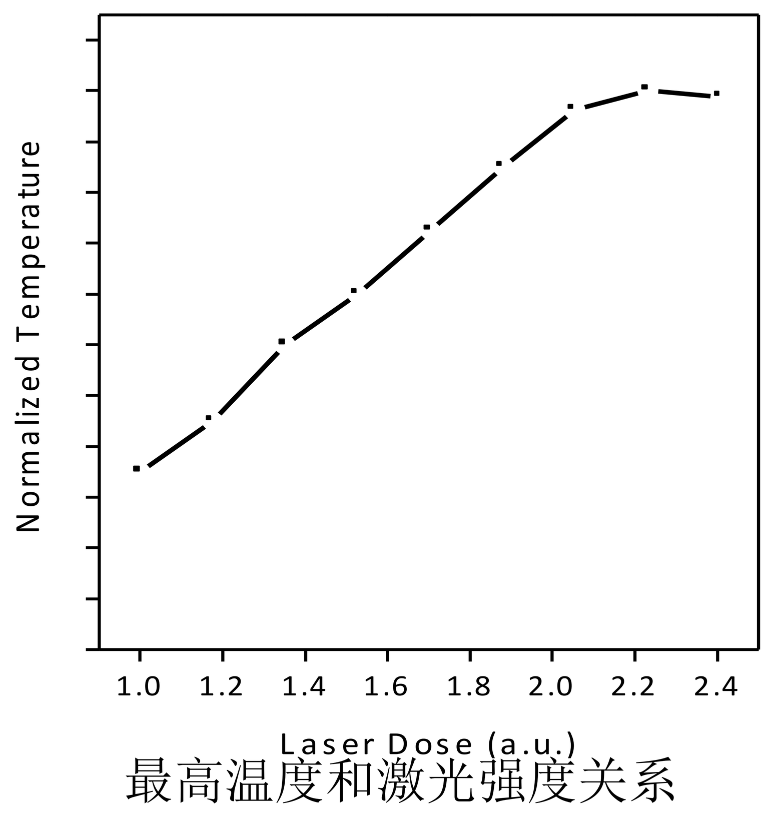
半导体材料的晶格常数和能带

Approach 方法

- Ge films are deposited by RF magnetron sputtering:
  Low cost / Environmentally friendly / Simple and scalable technique
  磁控溅射沉积锗薄膜：低成本、环保、简单、可大规模生产
- The laser used is continuous-wave diode laser with line-focus optics:
  Fast process with millisecond exposure time
  激光退火：快速的工序，仅需数毫秒的曝光时间



激光退火示意图



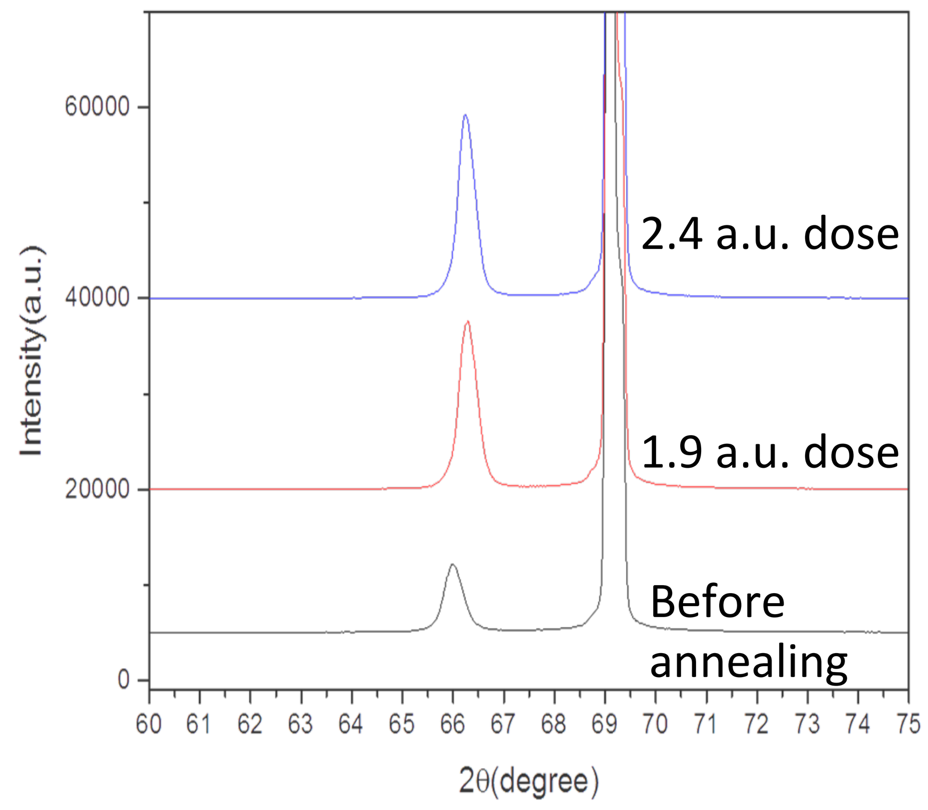
最高温度和激光强度关系

Results 实验结果

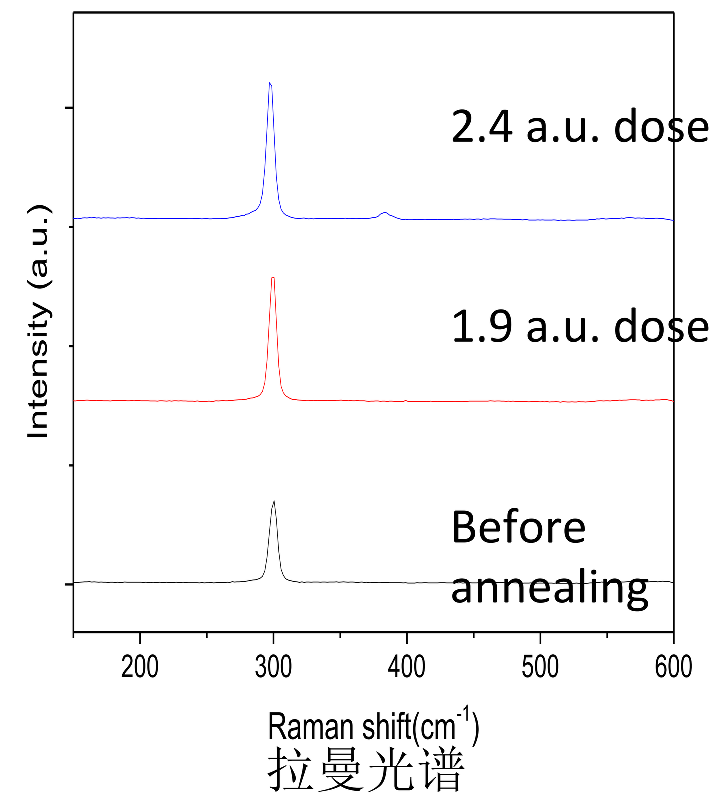
The peak temperature sharply rose with laser dose increasing from 1 a.u. to 2.4 a.u.. After that, the peak temperature saturated at a maximum value indicating partial melting of the film and absorption of latent heat.

随着激光能量从 1 a.u.增强到 2.4 a.u.，锗膜最高温度随之增长，直到达到极限值保持平稳，表明锗薄膜开始逐步融化并吸收潜热。

After laser annealing, the crystallinity of the Ge film is significantly improved as indicated by the XRD results. The Ge XRD peak intensity increases and the peak width reduces. X射线衍射测量结果显示，激光退后锗峰有所增强，表明结晶度提升。



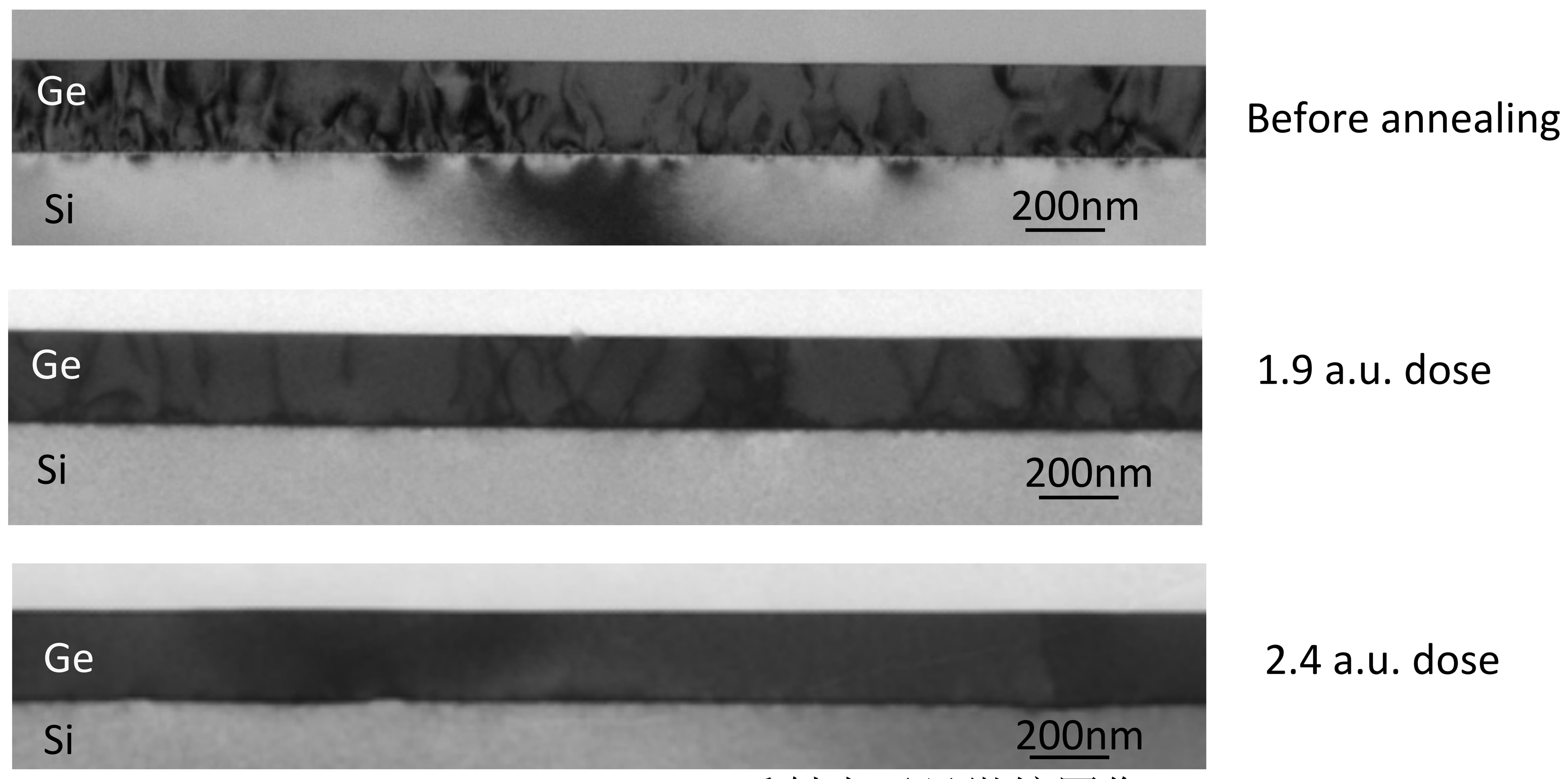
X射线衍射图谱



拉曼光谱

Raman spectra show improved crystallinity after laser annealing. The small Si-Ge peak in 2.4 a.u. dose sample suggests melting of Ge layer.

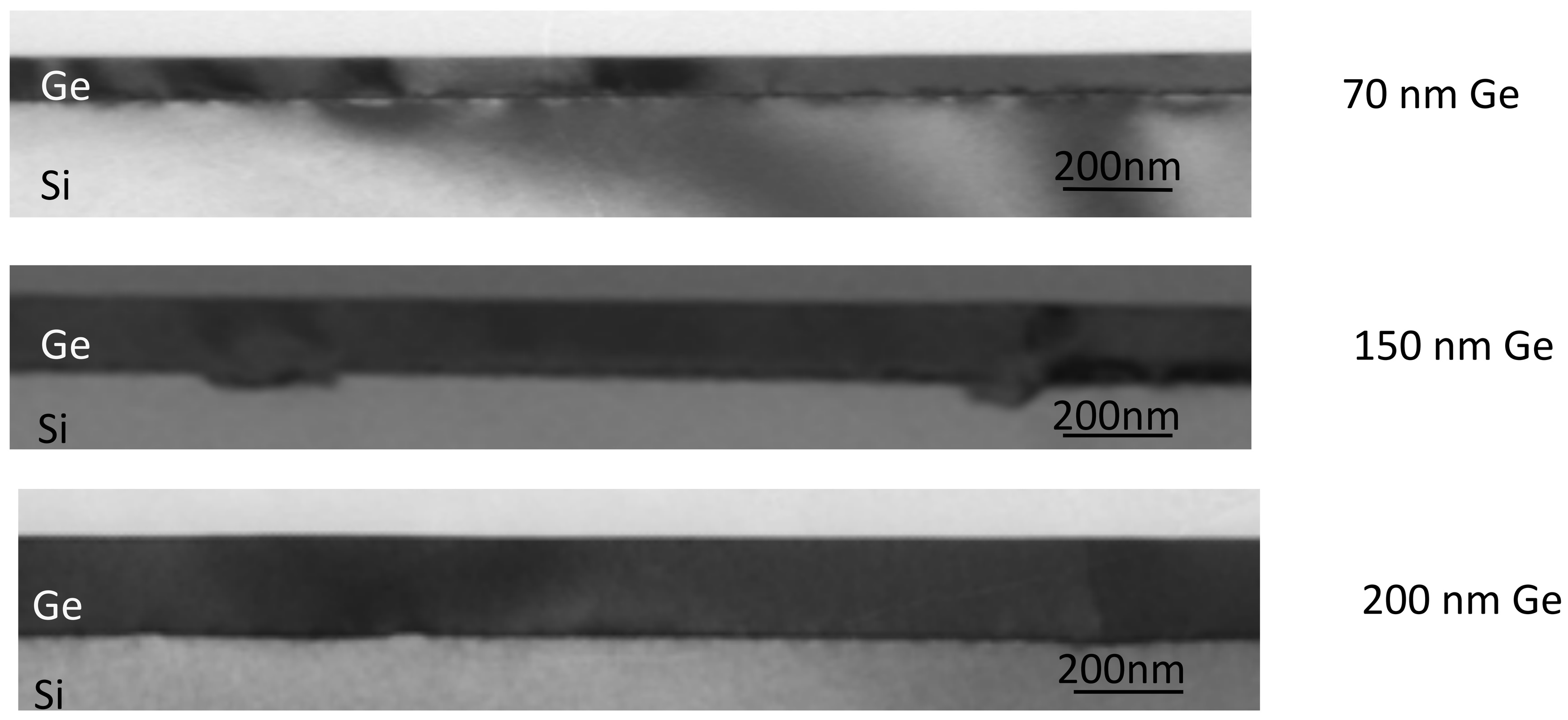
拉曼光谱显示锗结晶度有所提升，在高激光强度（2.4 a.u.）下锗薄膜已经融化并再结晶。



TEM images 透射电子显微镜图像

The reduction of TDD is revealed by TEM measurements. The as-deposited Ge film before annealing has a high TDD (10^{10} cm^{-2}). After laser annealing, the TDD can be reduced to 10^{6} cm^{-2} - 10^{7} cm^{-2} .

透射电子显微镜测量结果显示，激光退火显著降低了锗薄膜的位错缺陷密度，从沉积完未退火的高密度10^{10} cm^{-2} 大幅降低到10^{6} cm^{-2} - 10^{7} cm^{-2} 级别。



TEM images透射电子显微镜图像

Laser annealing has been applied on Ge layers with different thicknesses. High quality thin Ge layers with low TDD are obtained.

激光退火应用于多种厚度的锗薄膜（70-200纳米）均得到类似的低位错密度。

Conclusion 结论

Epitaxial Ge films have been grown on Si using magnetron sputtering which is low-cost, safe and scalable. Laser annealing is employed to effectively reduce the TDD in the Ge film. Laser annealing combined with magnetron sputtering offers a cost-effective approach to fabricate high quality virtual Ge substrates for high efficiency III-V solar cells.

磁控溅射和激光退火相结合可以制造出低成本高质量的虚拟锗衬底以用于高效率三五族太阳能电池

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