Single step optical realization of 3D photonic bandgap submicrometer periodic structures for thermophotovoltaics

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Outline of Presentation

- What is Thermophotovoltaics (TPV), its need and challenges?
- Simulation results for the design of absorber/emitter in TPV system.
- Bandgap calculation and study of optical properties.
- Experimental approach for realization of the designed structure.
- Experimental Results and discussion.
- Simulation results approaching the application of the fabricated structures.
- Conclusion.
- References.
Need of Thermophotovoltaic for Solar energy Harvesting

- Broad solar spectrum limits the efficiency of single junction PV. Only 1% of the total solar radiation is utilized for solar energy harvesting.
- Solar PV is based upon the energy that falls within the BG of material of PV (Si).
- Unabsorbed low energy and thermalized high energy photons limit the efficiency of PV (the Shockley Queisser limit).
- Multi-junction PV are costly to fabricate.

Challenge

- Broad spectrum of solar radiation can be utilized to enhance the emissivity using 2D and 3D PhC based absorbers and emitters that help in increasing the efficiency of photovoltaic cell.
What is thermophotovoltaic (TPV)?

Thermophotovoltaic system is a static platform of energy conversion that converts thermal energy to electrical energy.

Basic Components in TPV
- Thermal absorber/emitter
- Photovoltaic diode
- Spectral control component (Optical filter)

Advantages
- Less maintenance cost.
- High conversion efficiency of radiation to electricity with recycling of unabsorbed photons
- Non dependent on weather

Recent advance in TPV technology (Viking 29)
- Electric sports car powered using Thermophotovoltaic system
- By US DOE, with JX Crystals, WA
- Gallium antimonide PV surrounding
- Emitter heated at 1700 K. 95% efficient with 75KW mobility to generate INR Photon.
Photonic Crystal based TPV system

- 3D Photonic crystals such as inverse opals and woodpile PhCs can be used as absorber or emitter for TPV applications.
- In general 3D PhCs are fabricated by self assembly or DLW method following electroplating or electro less-plating.
- Fabrication technique are costly, time consuming and includes multi-steps.

P. Nagpal et.al. Nano Let., Vol. 8, 2008

Alternative approach to Fabricate 3D PhCs for TPV

Phase engineered Interference lithography (IL) technique using a spatial light modulator
( A computed phase mask is used to modulate the laser beam electronically in order to generate multiple beams for interference)

**Pros**
- Large area
- Single step
- Scalable
- Complex photonic structures

**Cons**
- Large area nanofabrication limited by pixel size of SLM

**Advanced or a modified phase engineering IL technique**
- Lesser Optical components
- Realization of nanoscale complex photonic structures

Simulated intensity profile due to the interference of 4+1 phase engineered plane beams in umbrella geometry

Resultant Intensity ($I$), $K$ vectors and Individual fields are as follows:

$$I(r) = \sum_{p=0}^{n} \left| E_p \right|^2 + \sum_{p=0}^{n} \sum_{q=0, p \neq q}^{n} E_p E_q^* \exp[i(K_p - K_q).r + i\delta\psi_{pq}]$$

$$K_m = k(i \cos \frac{2(m-1)\pi}{n} \sin \theta + j \sin \frac{2(m-1)\pi}{n} \sin \theta + k \cos \theta)$$

$$E_1 = \exp(i(K_1 \cdot r + \pi / 2)) \quad E_3 = \exp(i(K_3 \cdot r))$$

$$E_2 = \exp(i(K_2 \cdot r - \pi / 2)) \quad E_4 = \exp(i(K_4 \cdot r))$$
Band Structure of the woodpile photonic structure on photoresist with 4 number of layers.

Band structure in log Scale

Band structure in linear Scale

Band structure at Frequency points

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Woodpile photonic structure on photoresist with 24 layers: showing complete photonic bandgap

Band structure in log Scale

Band structure in linear Scale

Band structure at Frequency points
Band Structure of the tungsten woodpile photonic Structure showing broadband absorption

BG in Linear scale for 4 layers

BG in Linear scale for 24 layers

BG for 4 layers

BG for 24 layers

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Experimental setup to realize woodpile photonic structures with submicrometer periodicity over large area
Experimentally realized woodpile photonic structures over large area on positive photoresist

SEM image of the fabricated structure on AZ1518 with a periodicity of $a=605$ nm on AZ1518, inset (a) is the simulated intensity profile, inset (b) is the corresponding magnified SEM view.
Optical Properties of the designed structure for Tungsten
Proposed structure applicable as an absorber and emitter for thermophotovoltaics applications.

Periodicity, $a=1000$ nm
Width, $w=250$ nm
Periodicity along Z axis, $c=1414$ nm
Broad operation band = 600 nm to 1800 nm
Absorption peak (100%) at 800-950 nm
Concluding remarks

- A cost effective and rapid technique is approached for the fabrication of woodpile structures.
- Surface topography reveals realization of submicrometer periodic structures over large area.
- Even a low contrast 3D photonic woodpile structures show complete photonic bandgap.
- The structure can be used as an absorber or emitter in TPV system when transferred to a suitable thermally stable material such as tungsten.
- These structures can be used as selective frequency filters for TPV system when transferred to silicon or can be used as components in optical communication.
References

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