# **Stretchable and Flexible Silicon-based Solar Cell Arrays**

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- 90% of solar cells are made of Si.
- Si has good efficiency and reliability.
- Si is brittle, and fractures at 1% strain.
- Si panel can only be placed at roof top, ...

Objectives:

- Make Si stretchable
- Investigate the mechanics issues
- Seek innovative applications (e.g., e-eye camera, flexible solar cell, cardiac electrophysiology, ...)

## A Stretchable Form of Single-Crystal Silicon for High-Performance Electronics on Rubber Substrates

Dahl-Young Khang, 1,3,4 Hanqing Jiang, 2 Young Huang, 2\* John A. Rogers 1,2,3,4\*

We have produced a stretchable form of silicon that consists of submicrometer single-crystal elements structured into shapes with microscale, periodic, wavelike geometries. When supported by an elastomeric substrate, this "wavy" silicon can be reversibly stretched and compressed to large levels of strain without damaging the silicon. The amplitudes and periods of the waves change to accommodate these deformations, thereby avoiding substantial strains in the silicon itself. Dielectrics, patterns of dopants, electrodes, and other elements directly integrated with the silicon yield fully formed, high-performance "wavy" metal oxide semiconductor field-effect transistors, p-n diodes, and other devices for electronic circuits that can be stretched or compressed to similarly large levels of strain.

#### Khang, Jiang, Huang, and Rogers, Science 311, 2006

News agencies: United Press International,

. . .

Display at the *Tech Museum of Innovation, Silicon Valley, California* 



Fabricate thin ribbon Si device elements

Bond elements to prestrained elastomeric substrate PDMS

Peel back PDMS; flip over

Flat Si ribbon becomes buckled due to prestrained PDMS











Scanning electron micrograph

— 30°um

Optical image



## **Initial Buckling Analysis**

Khang, Jiang, Huang, Rogers, Science, 2006



• Excellent agreement with experiments without any fitting parameters.





#### Stretchable Silicon at The Tech, San Jose, CA



## **Electronic Eye Camera**

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

An electronic camera that shapes up like a

**I Fall** 

human eve

NATUR Scientists **NEURODEGENERATIVE** DISEASE Why the mouse is no model TECHNOLOGY FEATURE Gene expression analysis **ELLULAR AGEING** 

How yeast cells put the clock back

32

TV Networks: ABC, BBC, CBC, MSNBC, ...

News agencies: AFP (France), Reuters, United Press International. Xinhua, ...

Newspapers: Chicago Tribune, Daily Telegraph (UK), ...

Magazines: Discover Magazine, MIT Technology Review, Nature News & Views, Scientific American, U.S. News and World Report, ...

NSF Press Release

Ko et al., *Nature* 454, 2008

## **Fabrication Steps**



## Pop Up Si Structure: Experimental Images





Scanning electron micrograph

• The interconnects buckle to form "big wave" structure.

Ko et al., *Nature* 454, 2008



- The island remains almost flat and experiences small strains.
- The shape of interconnects agrees well with experiments.

## **Electronics on complex surfaces**









#### **Stretchable Circuits**



(PNAS 2008)

• Twistability 🗸

TV Networks: BBC, CBC, ....

Magazines: Discover Magazine, MIT Technology Review, Newsweek, Scientific American, ...

NSF Press Release

#### **Bendable and Transparent Silicon Photovoltaic Devices**







#### (Nature Materials 2008)

- User-definable transparency
- High degrees of mechanical flexibility
- Ultra-thin form factor micro-concentrator design
- Excellent reliability
- Good efficiency
- Inexpensive

TV Networks: *ABC, MSNBC,* ... News agencies: *Reuters, Xinhua,* ... Newspapers: *New York Times, People's Daily...* Magazines: *MIT Technology Review, Nature News & Views, Scientific American,* ...

(Nature Materials 2006) Department of Energy Press Release

#### Microscale, Inorganic Light Emitting Diode (iLED)











#### (Science 2009)

•Advantages: flexible, high brightness, long lifetime, bidirectional emission, inexpensive.

•Applications: wearable health monitor and diagnostics, biomedical imaging devices, ... TV Networks: ABC, BBC, MSNBC, ...

News agencies: Reuters, ...

Newspapers: Boston Globe, New York Times, ...

Magazines: MIT Technology Review, ...

#### **Cardiac/Neural Electrophysiology** (Science, 2010; Science Translational Medicine, 2010; Nature Materials, 2010)



monitoring and humanelectronics interaction

## **Conclusions and Recent Publications**

- -- Mechanics plays an important role in the development of flexible and stretchable technologies.
- **JMPS** (2008, 2009, 2010)
- Nano Letters (2007, 2008, 2009a,b, 2010)
- Nature (2008)
- Nature Materials (2006, 2008, 2010)
- Nature Nanotechnology (2006)
- **PNAS** (2007, 2008, 2009)
- **PRL** (2010)
- Science (2006, 2008, 2009, 2010)
- Science Translational Medicine (2010)

## Cover of NSF Budget Request to Congress for fiscal year 2011





EV 2011 BUDGET REQUEST TO CONGRESS "Researchers Yonggang Huang at Northwestern University and John Rogers at the University of Illinois at Urbana-Champaign have developed circuits that can stretch, bend and even twist! ...

Potential uses include flexible sensors, transmitters, and new photovoltaic and microfludic devices, as well as areas of medicine and athletics."

## **Global vs Local Buckling—1D Buckling**



Global buckling happens when the substrate is relatively thin and long; otherwise, local buckling happens.

## **Global vs Local Buckling—2D Buckling**



At a certain thickness of the thin film, for the same length and width of plate, local buckling occurs when the substrate is relatively thicker.

## **Single Crystal Si and Mother Wafer**



three layers are strongly bonded

silicon ribbons sitting on the mother wafer

# **Electric Performance**

Khang, Jiang, Huang, Rogers, Science, 2006



• Wavy Si does not affect the electric performance.

# Pixel Distribution: Compare with experiment



- The analytical results agree well with experiments
- The density change of pixels due to deformation is around 10%, which is fairly small
- The distribution of pixels after deformation is quite