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Performance Enhancement of Solid State Light Emission Device and Geometrically Confinement of Lighting Dots by Using Patterned Wafer Approaches

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Outline

- **Background & Motivation**
- **Effect of Si substrate in SSI-LED**
- **SSI-LED on patterned Si-substrate**
- **Summary**

Background & Motivation

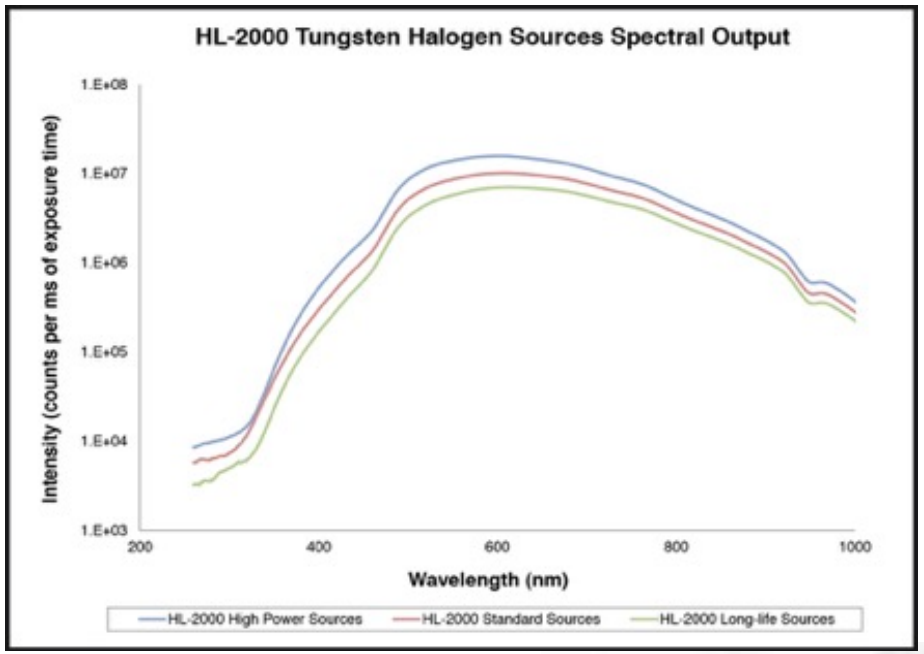
➢ Light source requirement for grating displacement sensor

- **Continuous spectrum**
- **Small in size**
- **Light in weight**

Typical source used before:

Tungsten Halogen Lamp

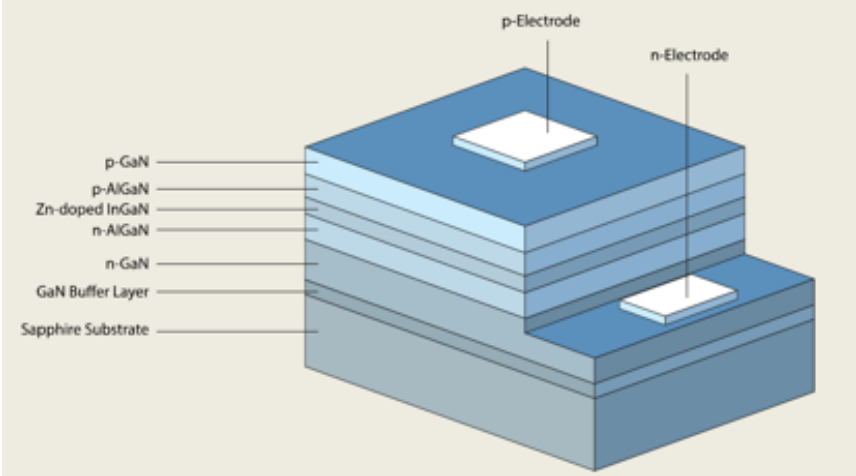
Real photos



Luminescence spectrum

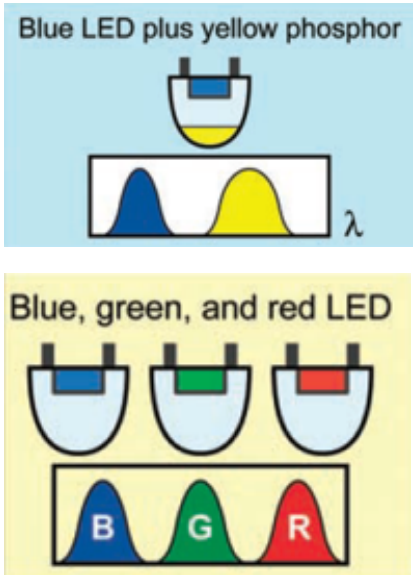
Background & Motivation

➢ Conventional LED



(Shuji Nakamura, et al. Appl. Phys. Lett. 1994)

White light



(E. Fred Schubert, et al. Science 2005)

Obtain white light

- **Blue LED+Yellow phosphor**
- **R+G+B LEDs**

Disadvantages

- **Complicated structure**
- **Narrow light spectrum （peaks）**
- **Low light intensity at red side**

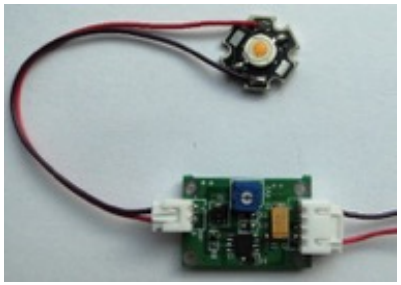
Background & Motivation

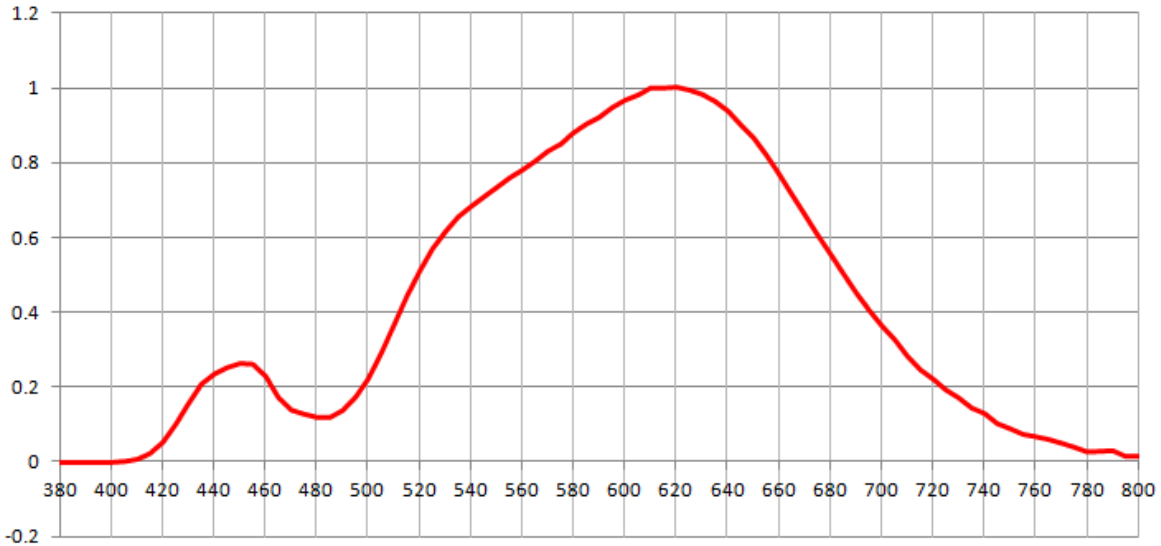
➢ Improvement of Luminescence spectrum for LED

LED:

- **Small in size**
- **Light in weight**

Luminescence spectrum need to be improved

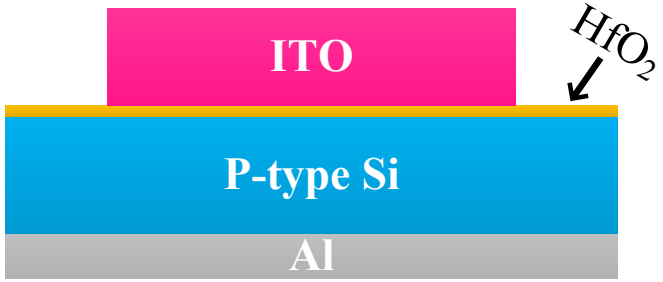




LED lamp & Its spectrum after adjusting the ratio of red phosphor

Background & Motivation

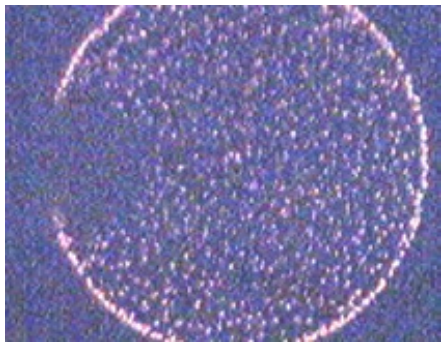
➢ Solid State Incandescent Light Emitting Device (SSI-LED)



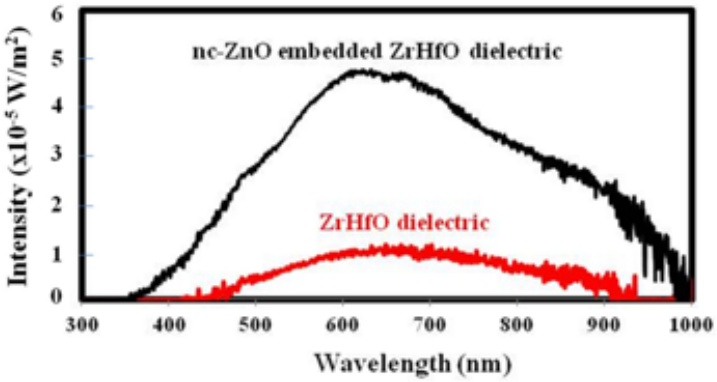
MOS structure

- **Broad band spectrum**
- **Light emission layer:**
  - ✓ **HfO_2 (key material)**
  - ✓ **HfO_2 + other materials**

Low resolution photo



Discrete lighting source

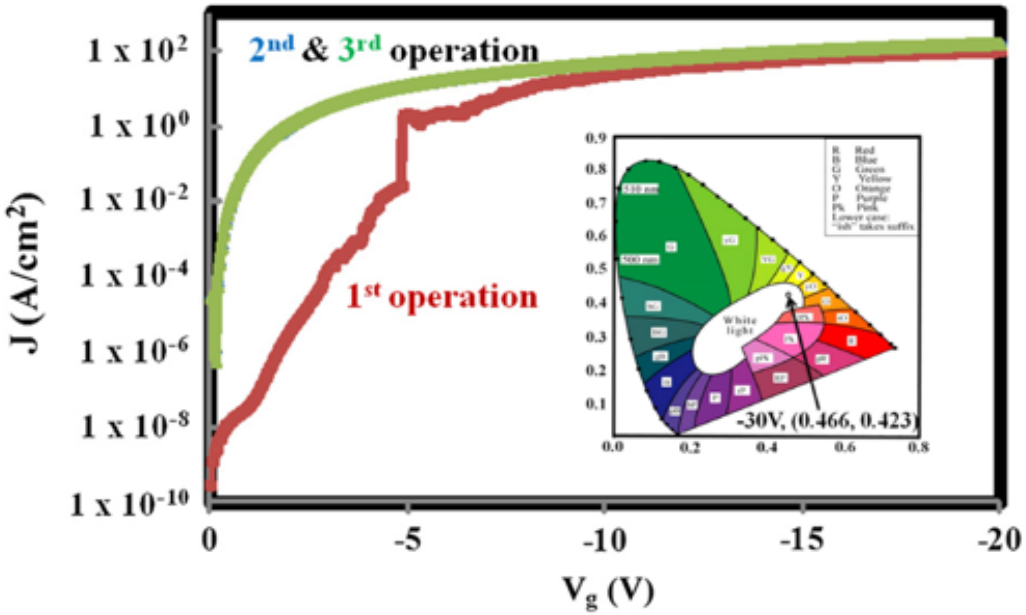


Emission spectra (broad band)

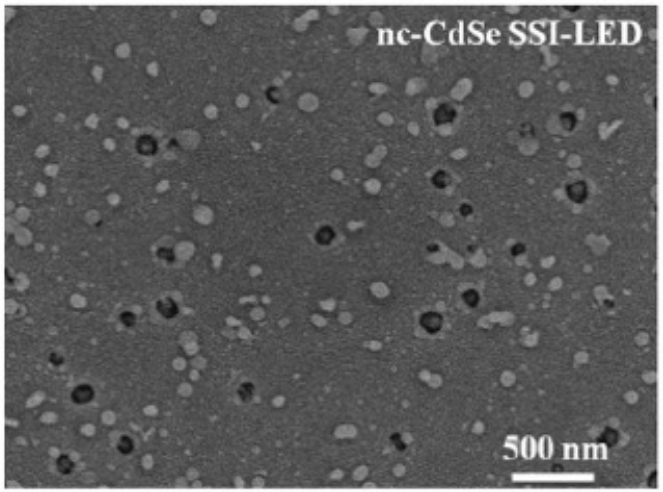
(Y Kuo, et al. Appl. Phys. Lett. 2013)

Background & Motivation

➢ Mechanism of SSI-LED



(Y Kuo, et al. Solid State Electronics. 2013)

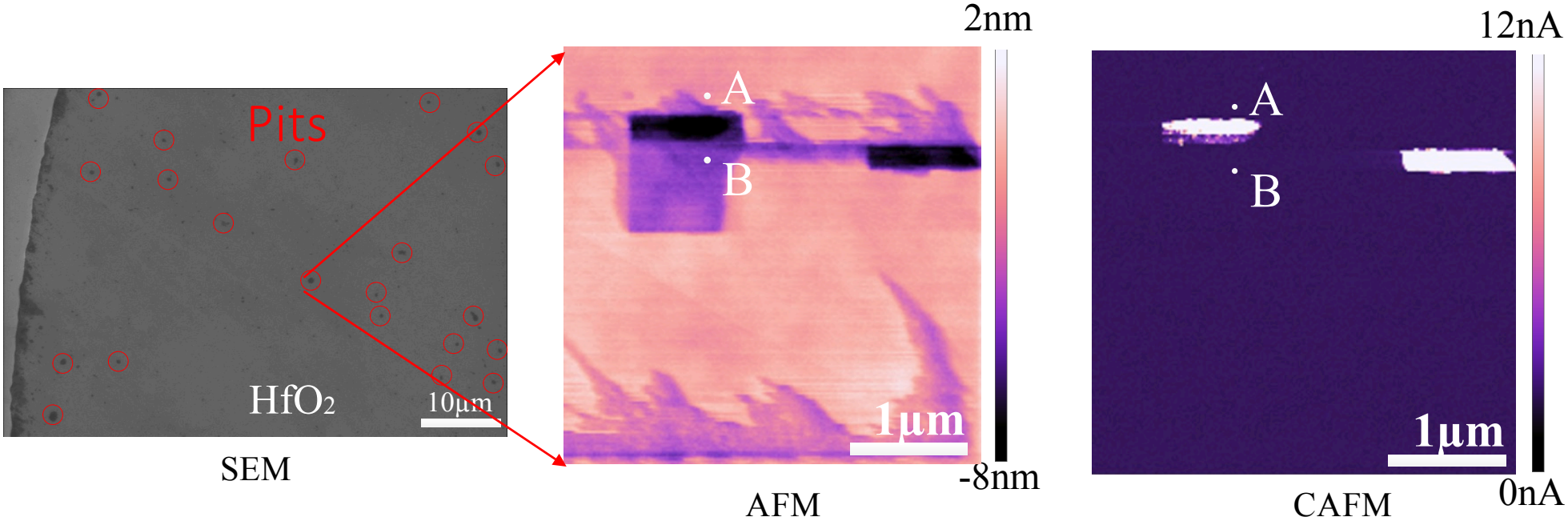


(Y Kuo, et al. Appl. Phys. Lett. 2015)

Luminescence comes from thermal excitation of current flowing through conductive filaments (CF).

Background & Motivation

➢ Mechanism of SSI-LED

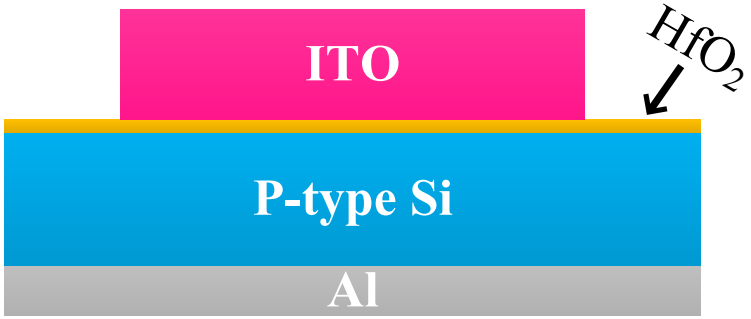


(Y Liu, et al. Nanotechnology. 2017)

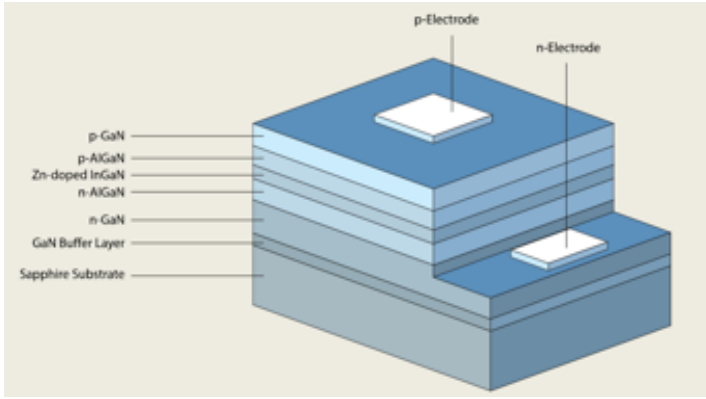
The conductive material in the pits is the conductive filament.

Background & Motivation

➢ SSI-LED vs LED



SSI-LED



LED

Advantages of SSI-LEDs

- **Simple MOS capacitor structure**
- **Light emission spectrum： from visible to IR ranges**
- **Low cost**
- **IC compatible processes**

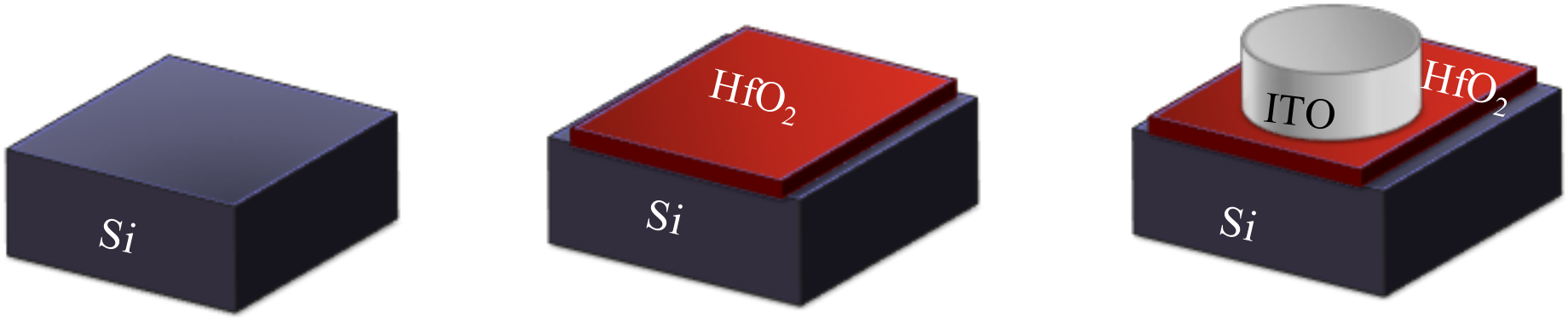
Outline

- Background & Motivation
- Effect of Si substrate in SSI-LED
- SSI-LED on patterned Si-substrate
- Summary

Effect of Si substrate in SSI-LED

➢ Fabrication process of SSI-LED

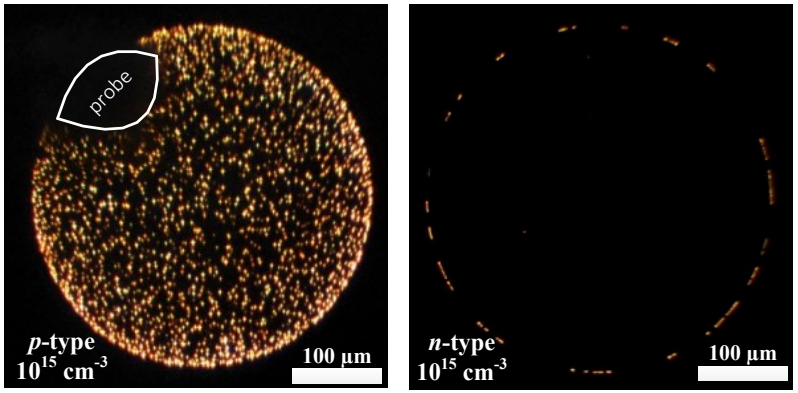
- Substrate cleaning： BOE solution (60s); acetone(5min); ethyl alcohol(5min)
- High-k layer： Sputtering Hf target, Ar:O_2=20:20, 100W, RT, 600 s
- ITO electrode: Sputtering ITO target, Ar:O_2=20:0, 70W, RT, 600 s
- ITO etching: aqua regia, 20s
- RTA： N_2, 400℃, 5min



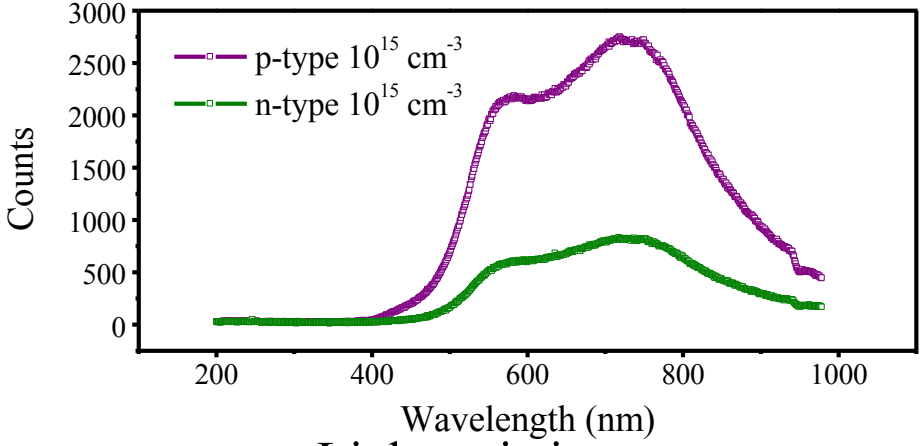
Effect of Si substrate in SSI-LED

➢ Effect of Si substrate doping type (p-Si & n-Si)

- **Characteristics of light emission**



Light emission photos



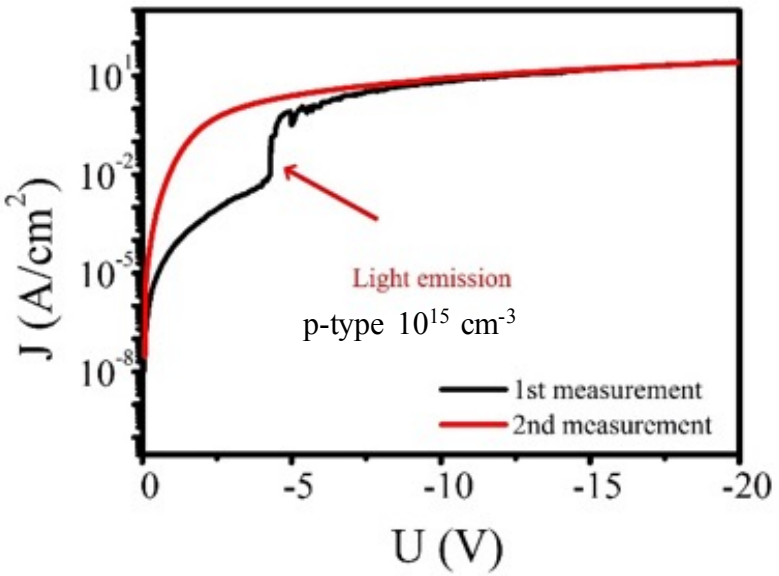
Light emission spectra

- ✓ **More lighting dots in p-Si device**
- ✓ **Brighter light generated in p-Si device**

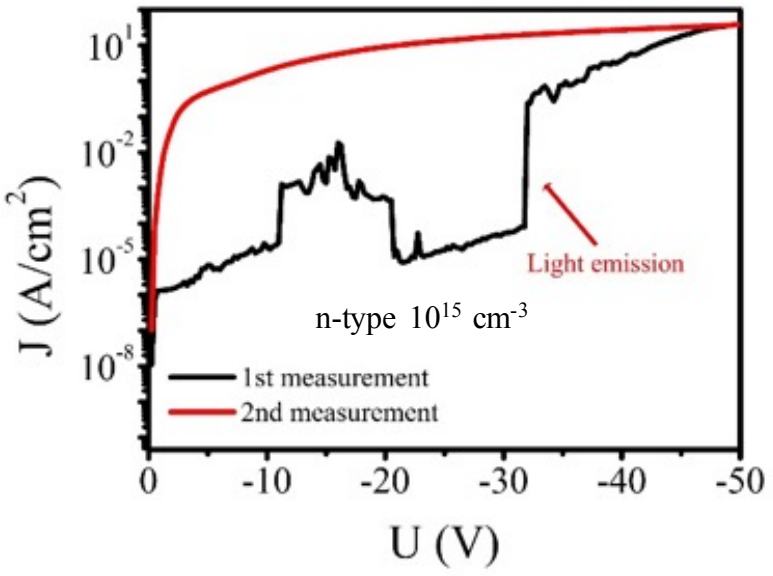
Effect of Si substrate in SSI-LED

- **Electrical properties**

J-V curve



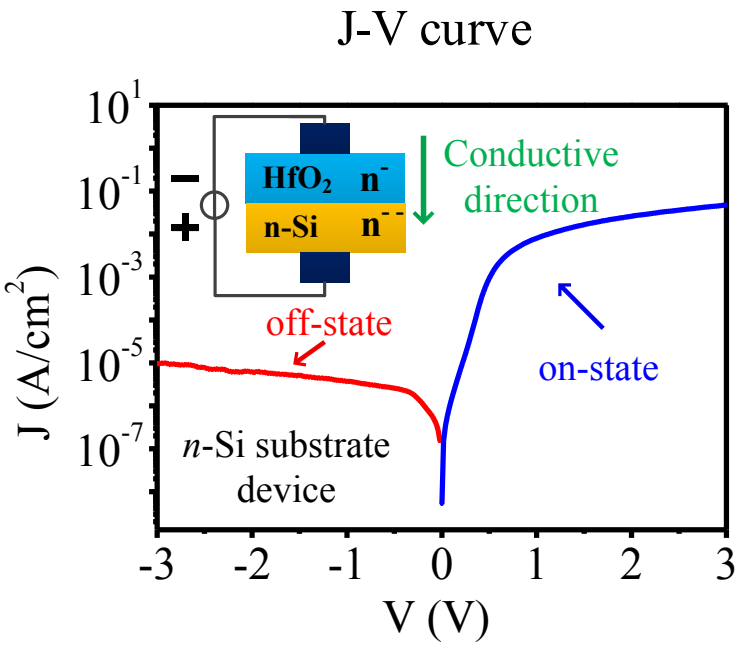
J-V curve

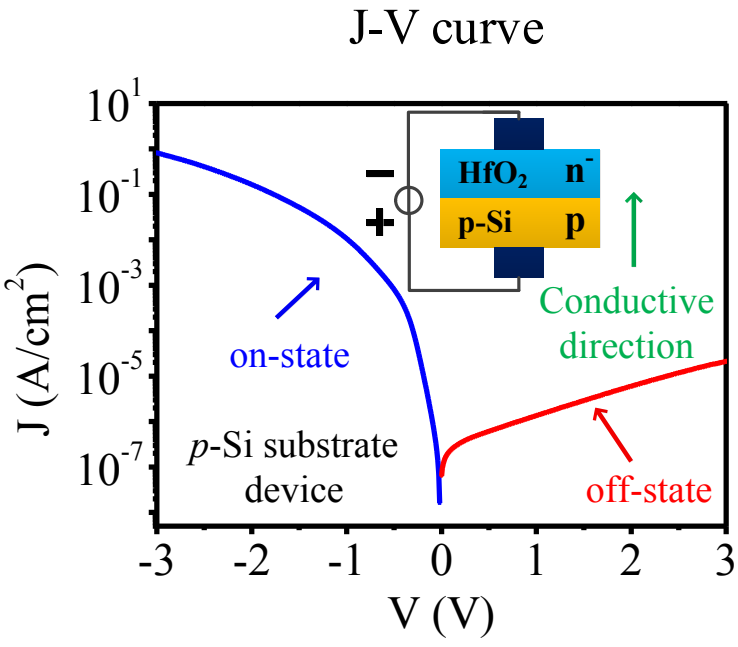


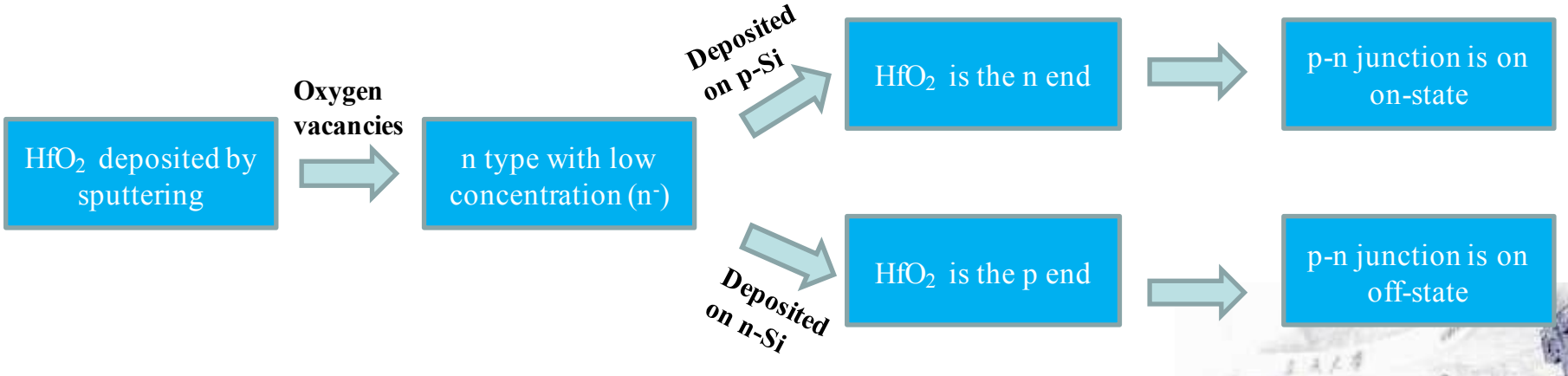
p-Si substrate:

- ✓ **Lower breakdown and working voltage**
- ✓ **More suitable for SSI-LED than n-Si**

Effect of Si substrate in SSI-LED



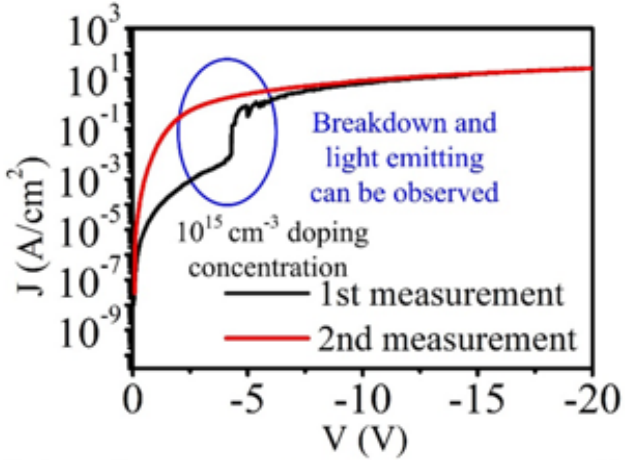


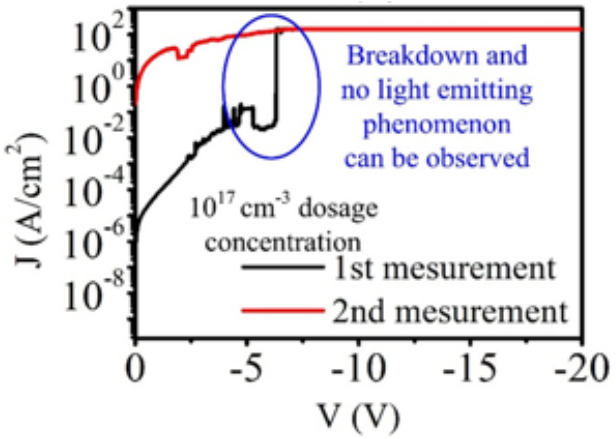


Effect of Si substrate in SSI-LED

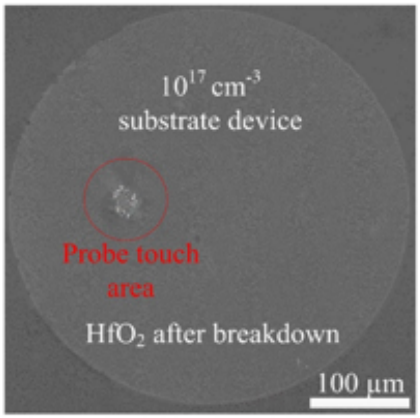
➢ Effect of doping concentrations of Si substrate

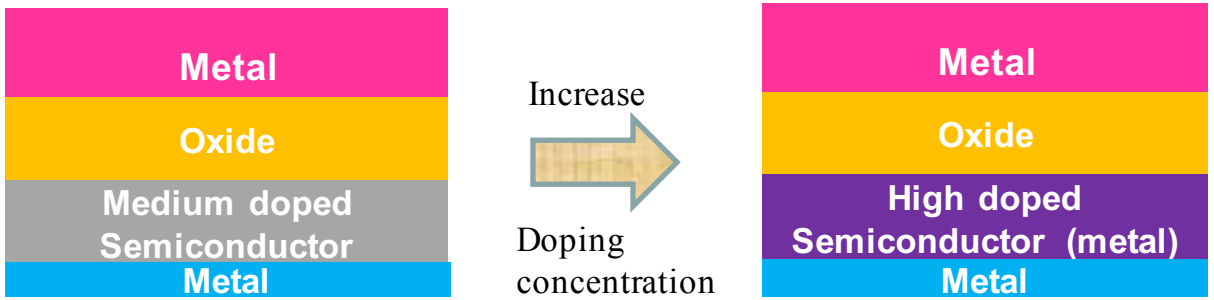
J-V curve





SEM





✓ **P-10^{15} cm^{-3} is the optimization parameter of Si substrate for SSI-LED.**

Outline

- Background & Motivation
- Effect of Si substrate in SSI-LED
- SSI-LED on patterned Si-substrate
- Summary

SSI-LED on patterned Si-substrate

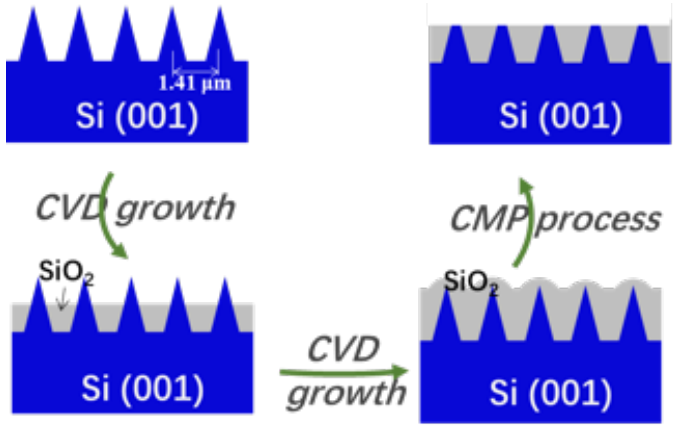
➢ Si substrates patterned in 2 different process

Electric field applied on HfO_2 can be enhanced by the patterned wafer

❑ Wet-etching process

Tetramethylammonium Hydroxide (TMAH) solution at room temperature by standing wet-etching. (distribution cannot be controlled)

❑ CMOS process



Si tips: Advanced lithography and reaction-ion-etching technologies

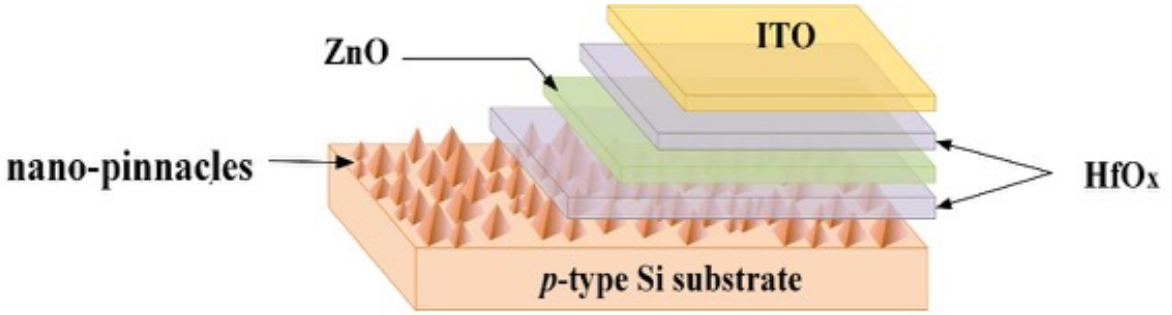
SiO_2 layer: CVD method

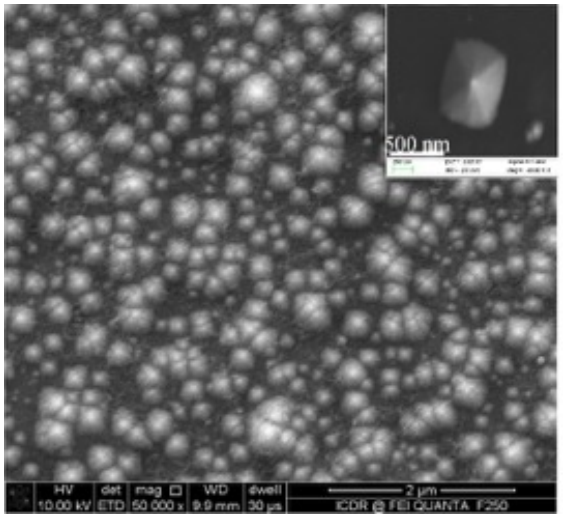
Stripes: Chemical mechanical polishing process

SSI-LED on patterned Si-substrate

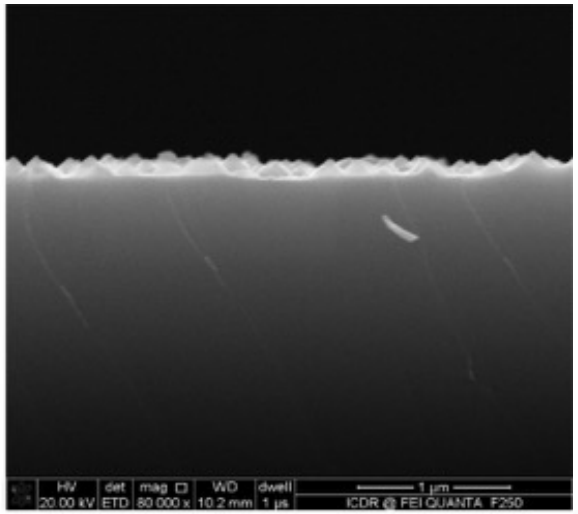
➢ Si substrate patterned randomly using wet-etching process (1)

- **Device structure**





SEM: surface

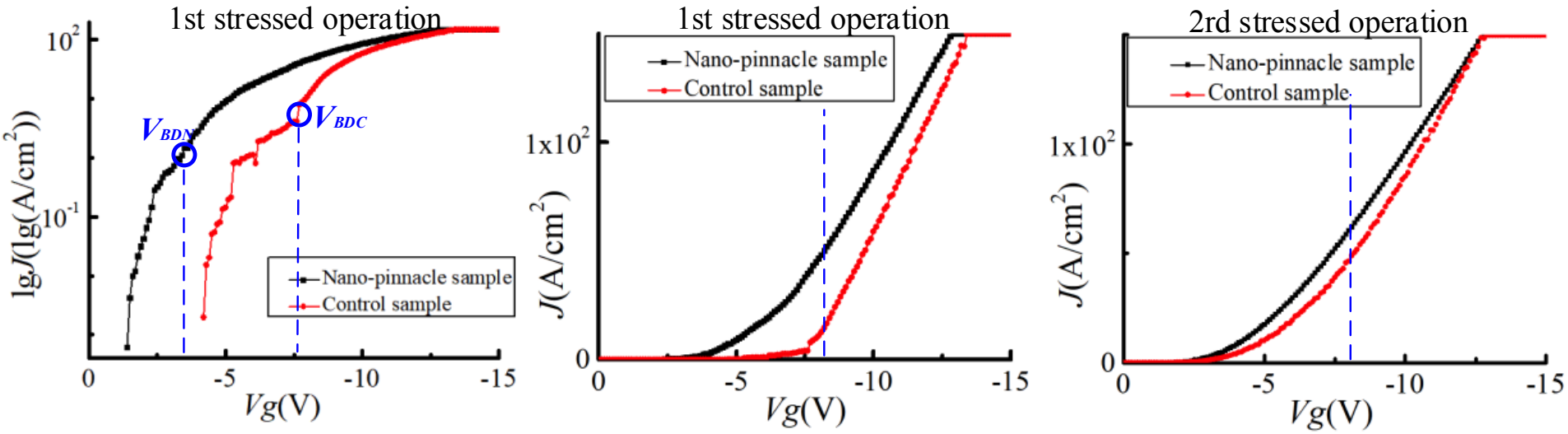


SEM: section

SSI-LED on patterned Si-substrate

➢ Si substrate patterned randomly using wet-etching process (2)

- **Electrical characteristic**



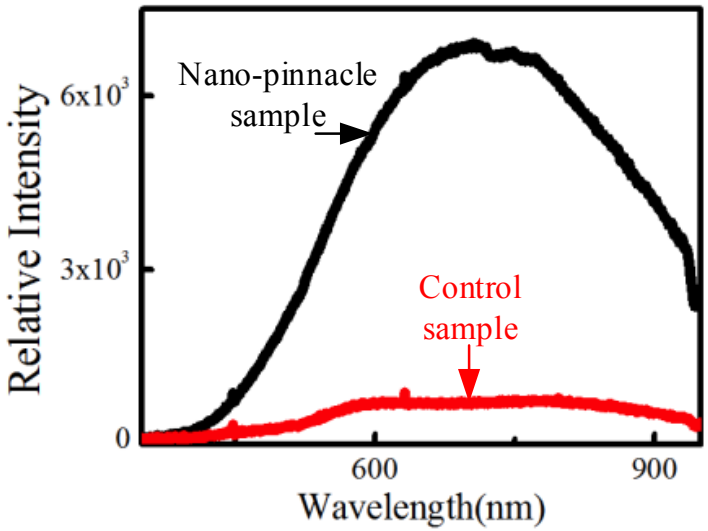
J-V curves of the nano-pinnacles substrate and reference device

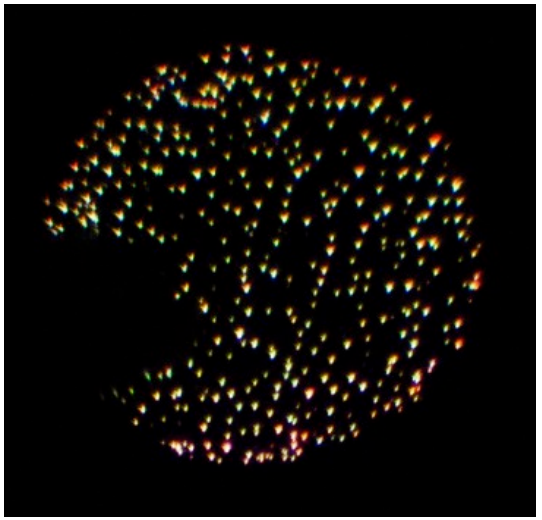
The nano-pinnacles substrate device has a lower breakdown voltage and larger working current density than the reference device.

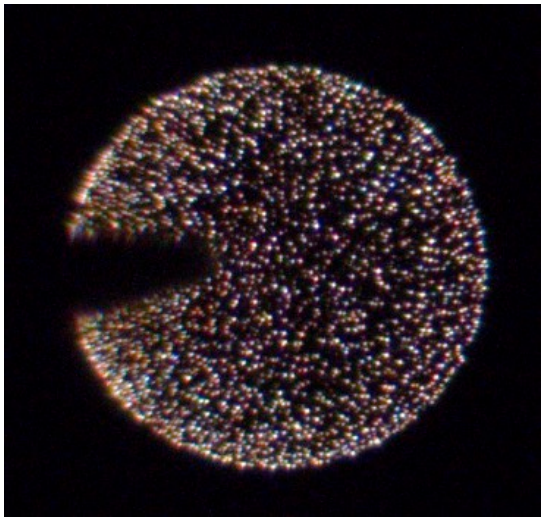
SSI-LED on patterned Si-substrate

➢ Si substrate patterned randomly using wet-etching process (3)

- **Optical characteristic**







Control sample　　Nano-pinnacle sample

Lighting spectrum and photo of the nano-pinnacles substrate and reference device

Lighting dot density:

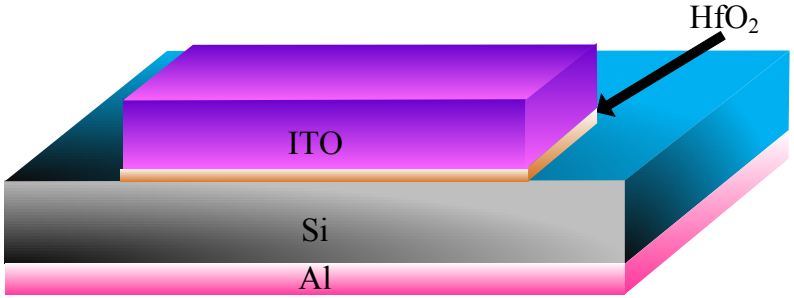
$0.8\times10^3/cm^2$ (reference device) and $6.9\times10^3/cm^2$ (nano-pinnacles device)

More lighting dots and brighter in nano-pinnacles substrate device.

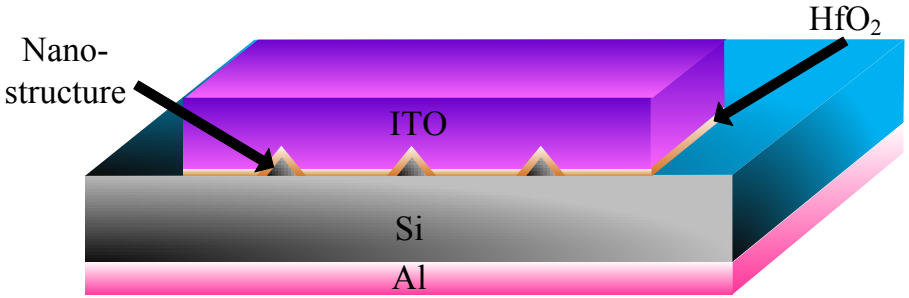
SSI-LED on patterned Si-substrate

➢ Si substrate patterned regularly using CMOS processing (1)

- **Device structure**

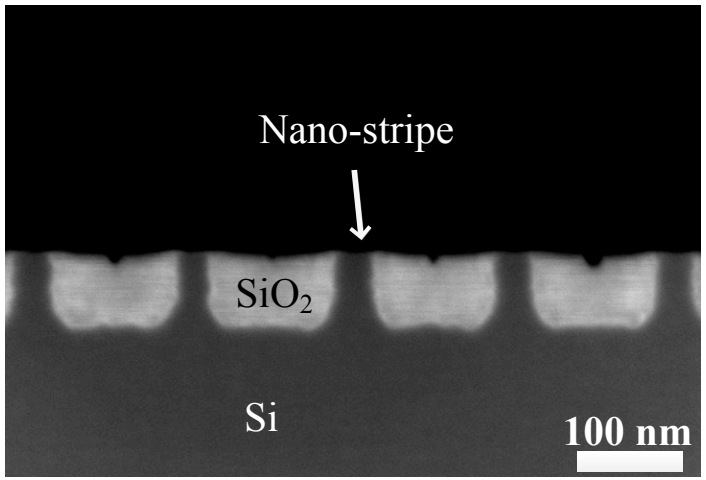


Reference sample

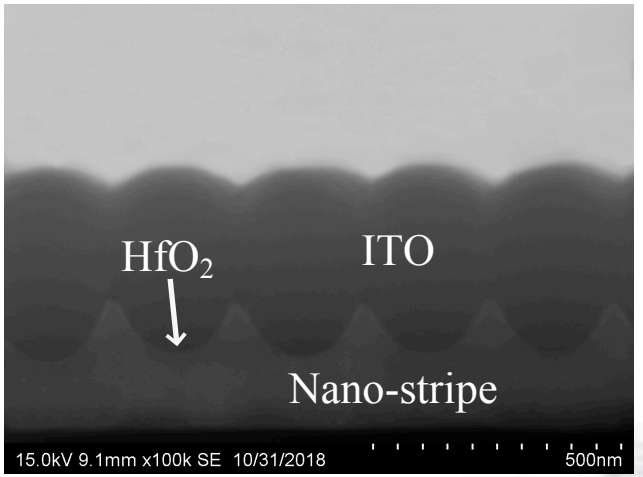


Nano-structure device

SEM image



Only substrate



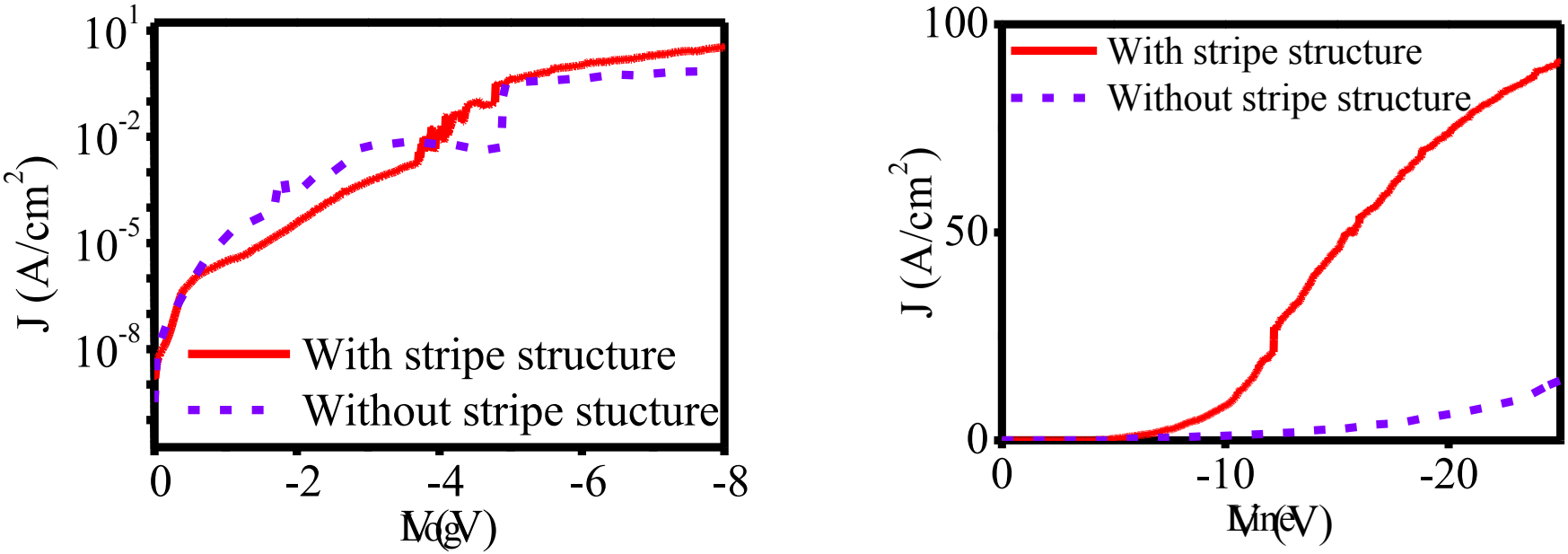
Substrate and device

Parameter of nano-stripe:
Height:100 nm
Width: 150 nm
Interval: 100 nm

SSI-LED on patterned Si-substrate

➢ Si substrate patterned regularly using CMOS processing (2)

- **Electrical characteristic**



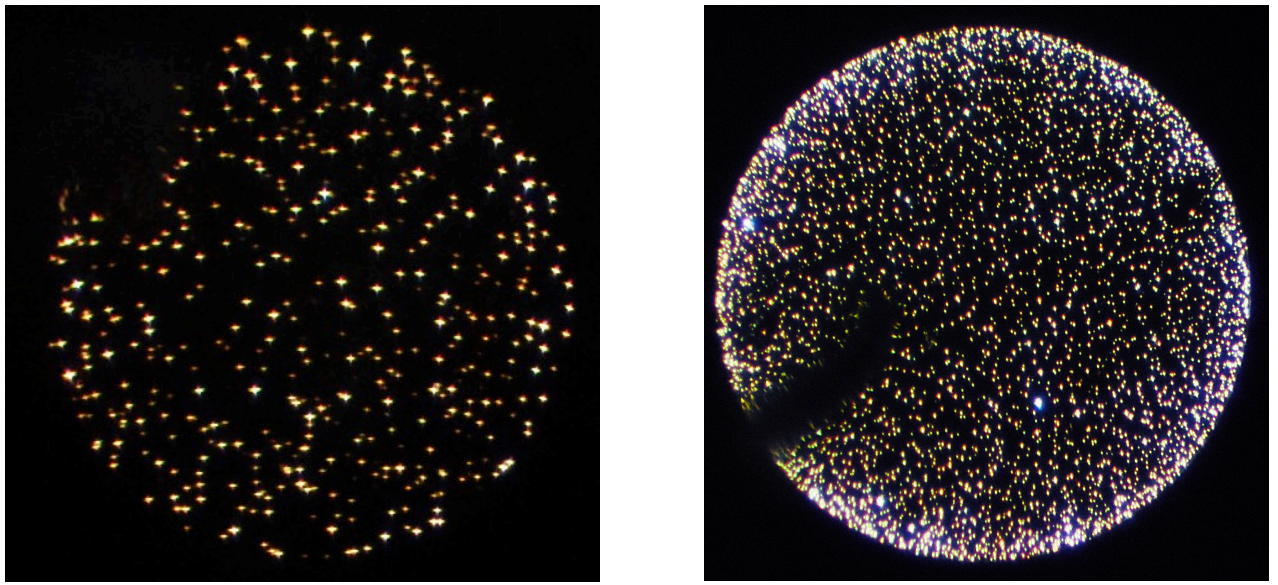
J-V curves of the nano-stripe substrate and reference device

Nano-stripe device can breakdown and work under lower voltage.

SSI-LED on patterned Si-substrate

➢ Si substrate patterned regularly using CMOS processing (3)

- **Optical characteristic**



Reference sample　　Nano-stripe device

Lighting photo of the nano-stripe substrate and reference device

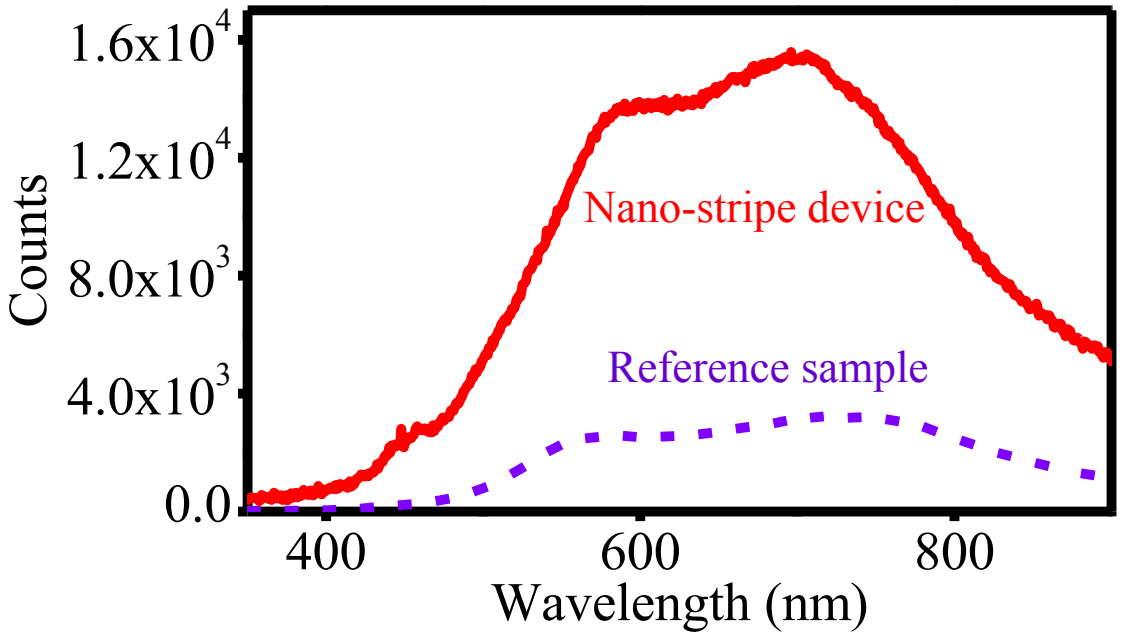
Lighting dot density: $2.66\times10^{6}/cm^{2}$ **vs** $2.02\times10^{7}/cm^{2}$

Lighting dots still distribute in a random way.

SSI-LED on patterned Si-substrate

➢ Si substrate patterned regularly using CMOS processing (4)

- **Optical characteristic**



Lighting spectra of nano-stripe and reference device

More lighting dots and stronger light generated in nano-stripe device

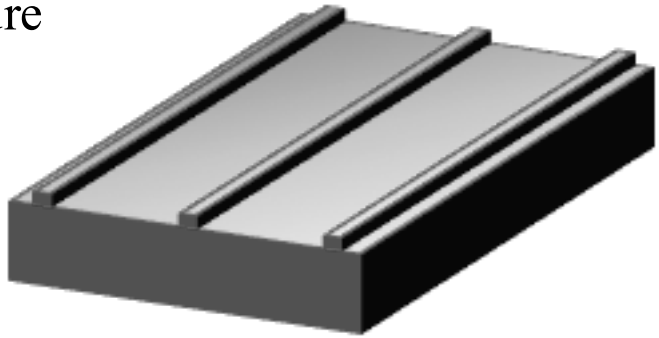
The properties of SSI-LED are improved by using nano-stripe substrate
Distribution of lighting dots still can not be controlled.

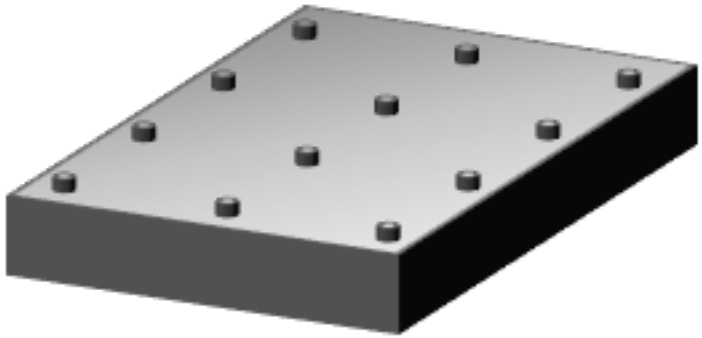
SSI-LED on patterned Si-substrate

➢ Si substrate patterned regularly using CMOS processing (5)

- **Micrometer size stripe substrate device**

Substrate structure

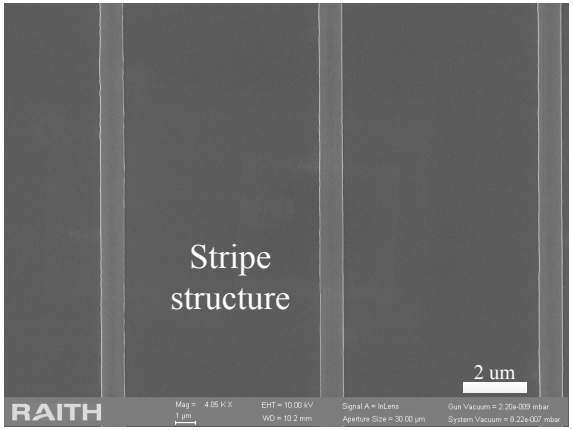


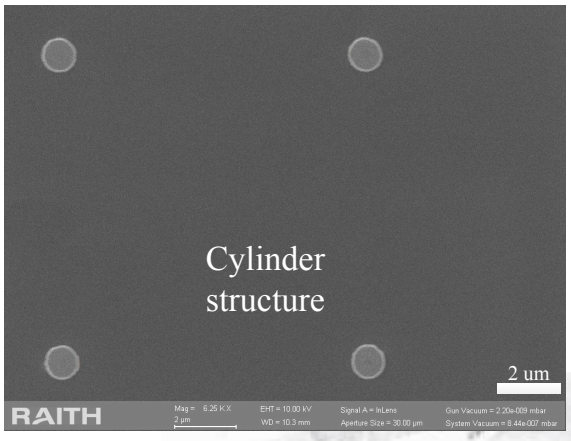


1 μ m width, 8 μm interval

1 μm diameter, 8 μm interval

SEM image

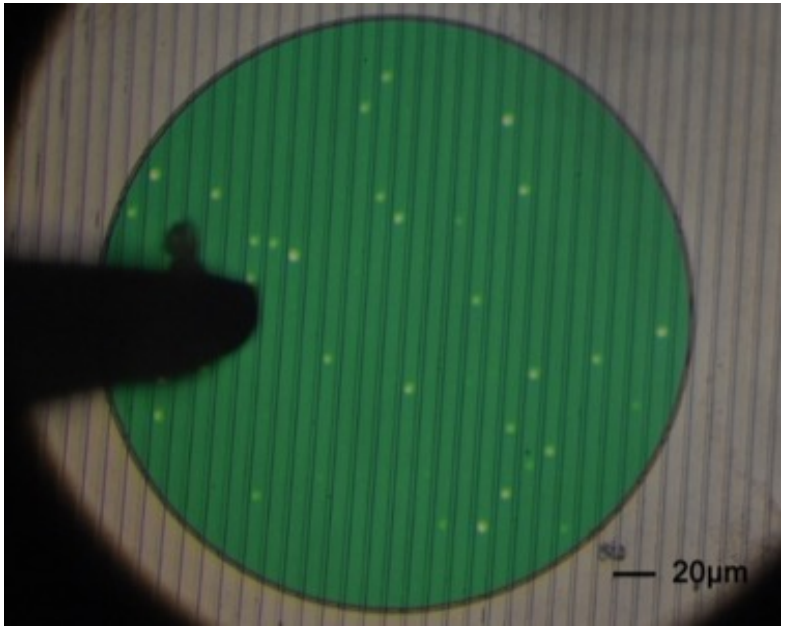




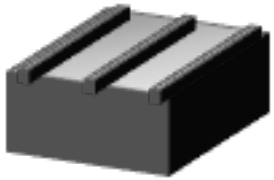
SSI-LED on patterned Si-substrate

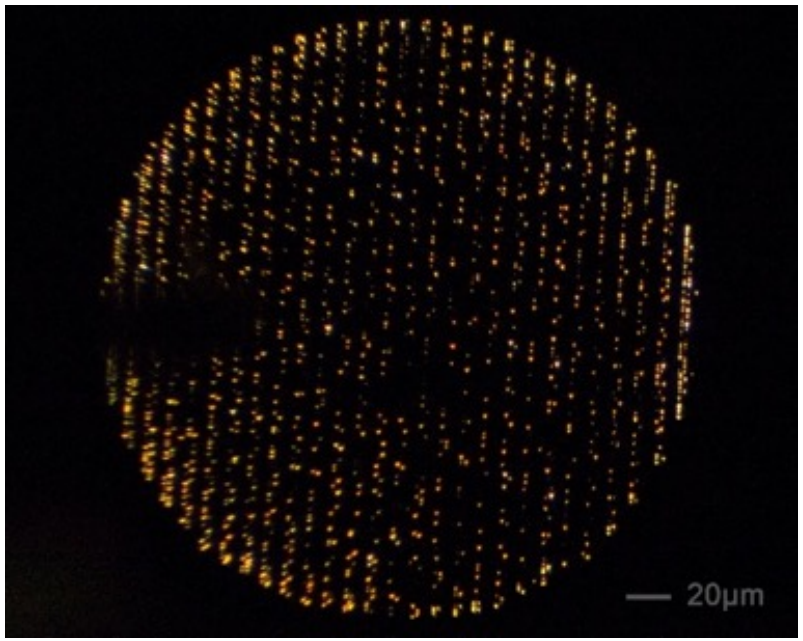
➢ Si substrate patterned regularly using CMOS processing (6)

- **Micrometer size stripe substrate device**



Before lighting





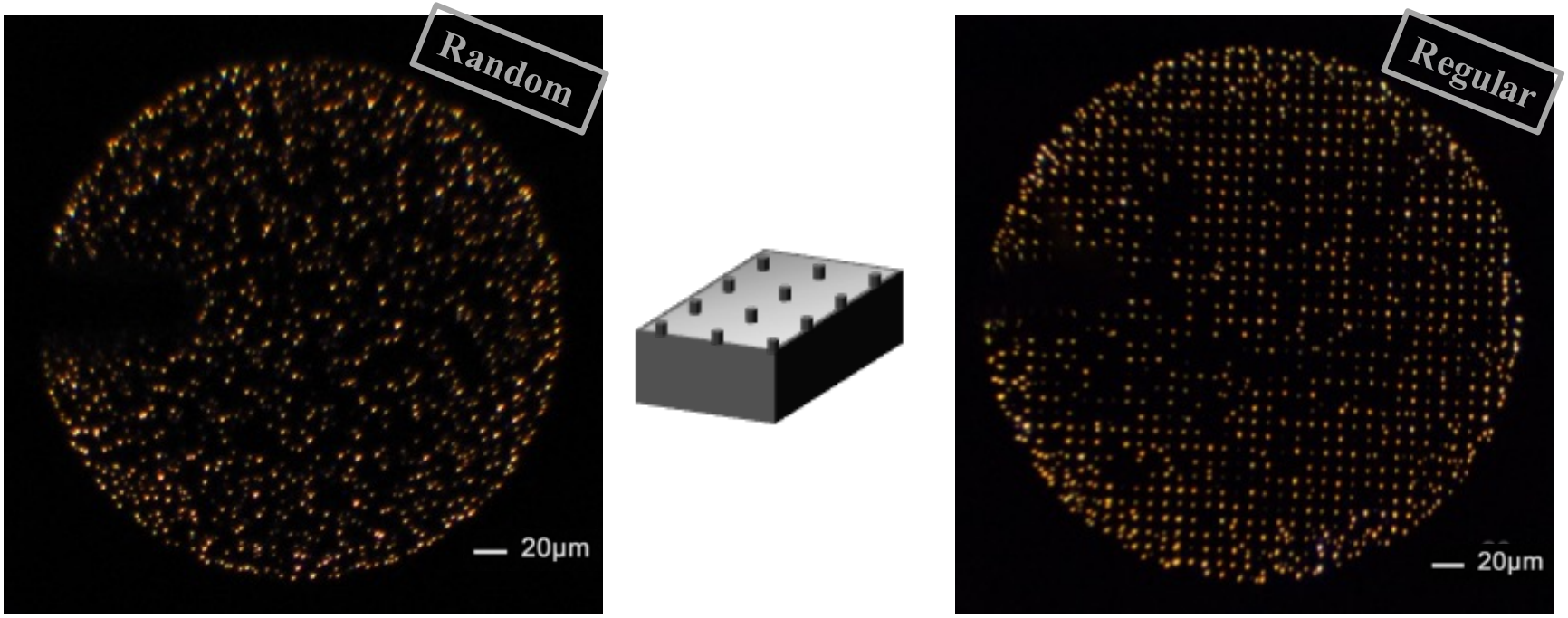
lighting

Lighting photos of the micrometer size stripe substrate device

SSI-LED on patterned Si-substrate

➢ Si substrate patterned regularly using CMOS processing (6)

- **Micrometer size stripe substrate device**



Lighting photo of the micrometer size cylinder substrate and reference device

Generally conductive filaments appear randomly. For devices fabricated on substrates with micrometer size structure, the arrangement of bright dots coincides with the nanostructure array on the substrate.

Outline

- Background & Motivation
- Effect of Si substrate in SSI-LED
- SSI-LED on patterned Si-substrate
- Summary

Summary

- The doping type and concentration of Si substrate has significant effects on performance of the device. The p-10^{15} cm^{-3} Si wafer is a superior substrate candidate for the SSI-LEDs.

- The electrical and optical characteristics of SSI-LED were optimized with the use of two nanometer size structures, nano-pyramid and nano-stripe, fabricated on Si substrate.

- The surface structure patterned regularly on substrate with a micro-meter size has been verified to be in great capacity for the lighting dots distribution control.

Acknowledgements

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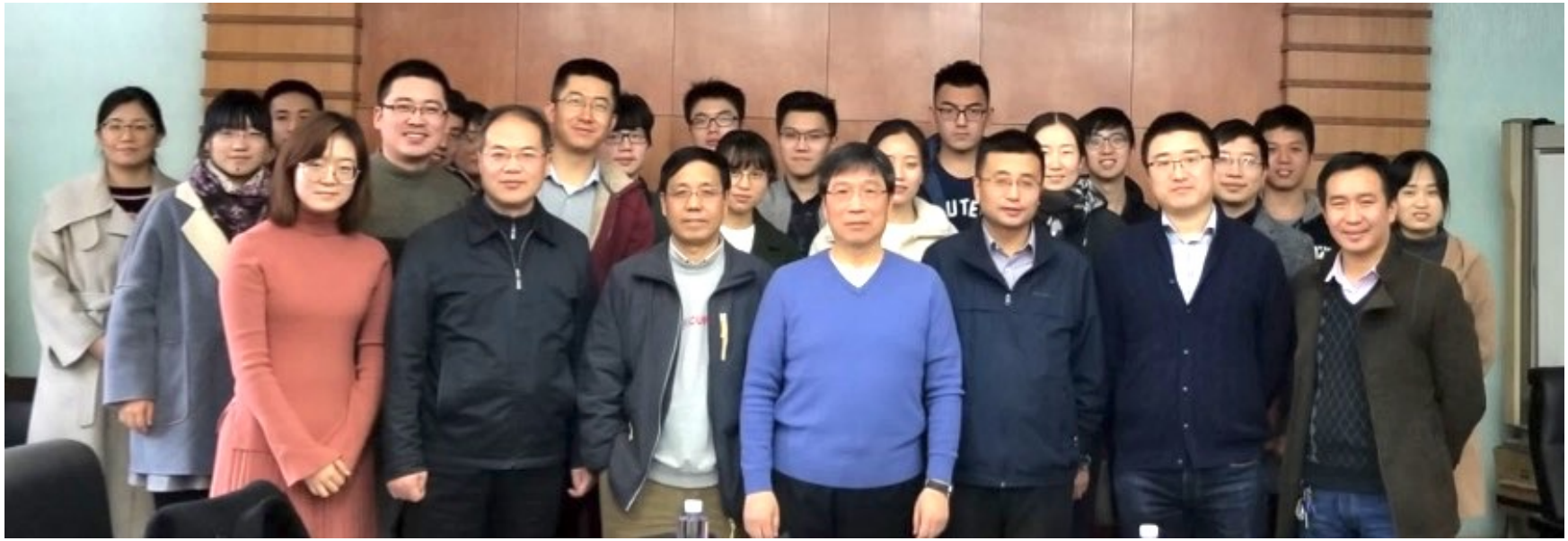

Thank you for your kind attention!