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Shengli Wu, Yiwei Liu, Xiaoning Zhang, Can Yang, Lingguang Liu, Yaogong Wang, and Gang Niu
Performance Enhancement of Solid State Light Emission Device and Geometrically Confinement of Lighting Dots by Using Patterned Wafer Approaches

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ULSIC vs. TFT VII, Kyoto, Japan, May 19-23, 2019
Outline

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


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
Solid State Incandescent Light Emitting Device (SSI-LED)

- Broad band spectrum
- Light emission layer:
  - HfO$_2$ (key material)
  - HfO$_2$ + other materials

MOS structure

Low resolution photo  Discrete lighting source  Emission spectra (broad band)


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Background & Motivation

➢ Mechanism of SSI-LED


Luminescence comes from thermal excitation of current flowing through conductive filaments (CF).
The conductive material in the pits is the conductive filament.

(Y Liu, et al. Nanotechnology. 2017)
SSI-LED vs LED

Advantages of SSI-LEDs
- Simple MOS capacitor structure
- Light emission spectrum: from visible to IR ranges
- Low cost
- IC compatible processes
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**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°C, 5min
Effect of Si substrate in SSI-LED

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

- Characteristics of light emission

- More lighting dots in p-Si device
- Brighter light generated in p-Si device
Effect of Si substrate in SSI-LED

- Electrical properties

**p-Si substrate:**
- Lower breakdown and working voltage
- More suitable for SSI-LED than n-Si
Effect of Si substrate in SSI-LED

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Effect of Si substrate in SSI-LED

Effect of doping concentrations of Si substrate

![J-V curve](image)

- $10^{15}$ cm$^{-3}$ doping concentration
- Breakdown and light emitting can be observed
- 1st measurement
- 2nd measurement
- $10^{17}$ cm$^{-3}$ dosage concentration
- Breakdown and no light emitting phenomenon can be observed
- 1st measurement
- 2nd measurement

SEM

- $10^{17}$ cm$^{-3}$ substrate device
- Probe touch area
- HfO$_2$ after breakdown

Metal

Oxide

Medium doped Semiconductor

Metal

Doping concentration

Increase

Metal

Oxide

High doped Semiconductor (metal)

Metal

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

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SSI-LED on patterned Si-substrate

- Si substrates patterned in 2 different process

  Electric field applied on HfO₂ 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

    SiO₂ 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

![Device Structure Diagram]

- ZnO
- ITO
- HfOx
- p-type Si substrate
- nano-pinnacles

SEM: surface
SEM: section

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

- Electrical characteristic

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

Control sample

Nano-pinnacle sample

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

**Lighting dot density:**

\[ 0.8 \times 10^3 / \text{cm}^2 \text{ (reference device) and } 6.9 \times 10^3 / \text{cm}^2 \text{ (nano-pinnacles device)} \]

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

**Optical characteristic**

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

**SSI-LED on patterned Si-substrate**

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Si substrate patterned regularly using CMOS processing (1)

- **Device structure**

**Reference sample**

**Nano-structure device**

**SEM image**

Parameter of nano-stripe:
- Height: 100 nm
- Width: 150 nm
- Interval: 100 nm
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.
Si substrate patterned regularly using CMOS processing (3)

- Optical characteristic

Lighting photo of the nano-stripe substrate and reference device

**Lighting dot density:** $2.66 \times 10^6$/cm$^2$ vs $2.02 \times 10^7$/cm$^2$

Lighting dots still distribute in a random way.
Si substrate patterned regularly using CMOS processing (4)

- Optical characteristic

The properties of SSI-LED are improved by using nano-stripe substrate.

Distribution of lighting dots still cannot be controlled.
SSI-LED on patterned Si-substrate

- Si substrate patterned regularly using CMOS processing (5)
  - Micrometer size stripe substrate device

Substrate structure

SEM image

1 μm width, 8 μm interval

1 μm diameter, 8 μm interval

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Si substrate patterned regularly using CMOS processing (6)

- Micrometer size stripe substrate device

Lighting photos of the micrometer size stripe substrate device
Si substrate patterned regularly using CMOS processing (6)

- Micrometer size stripe substrate 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.
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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.
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