Slow Positron Spectroscopy – Applications to the Semiconductor Industry

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ION IMPLANTATION

EPITAXIAL GROWTH

LOW-K DIELECTRICS

SILICON PHOTONIC DETECTORS

THE FUTURE
ION IMPLANTATION

Defects in MeV Si-implanted Si probed with positrons

Bent Nielsen
Department of Applied Science, Brookhaven National Laboratory, Upton, New York 11973

J. Appl. Phys. 74 (3), 1 August 1993

Western Aug2016
Low energy implantation produces defects that interact with the surface.

Under certain conditions it is possible to remove the defects.
ION IMPLANTATION – DOSIMETRY

Simple expression for vacancy concentrations at half ion range following MeV ion implantation of silicon

P. G. Coleman, C. P. Burrows, and A. P. Knights

APPLIED PHYSICS LETTERS
VOLUME 80. NUMBER 6
11 FEBRUARY 2002

<table>
<thead>
<tr>
<th>Ion species</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45 MeV H⁺</td>
<td>1.20 × 10⁻⁴</td>
</tr>
<tr>
<td>1.5 MeV B⁺</td>
<td>3.16 × 10⁻²</td>
</tr>
<tr>
<td>2.0 MeV O⁺</td>
<td>6.64 × 10⁻²</td>
</tr>
<tr>
<td>2.0 MeV Si⁺</td>
<td>2.01 × 10⁻¹</td>
</tr>
<tr>
<td>4.0 MeV Ge²⁺</td>
<td>5.29 × 10⁻¹</td>
</tr>
</tbody>
</table>
Distribution of point defects in Si(100)/Si grown by low-temperature molecular-beam epitaxy and solid-phase epitaxy.

- Mean Depth (nm) vs. Beam Energy (keV)
- Normalized S parameter vs. Beam Energy (keV)
- Current density (A/cm²) vs. Voltage (V)

- $T_{RTA} = 450 ^\circ C$
- $T_{RTA} = 500 ^\circ C$
- $T_{RTA} = 600 ^\circ C$
- $T_{growth} = 220 ^\circ C$
EPITAXIAL GROWTH

Growth temperature dependence for the formation of vacancy clusters in Si/Si 0.64 Ge 0.36 /Si structures

A. P. Knights, R. M. Gwilliam, B. J. Sealy, T. J. Grasby, C. P. Parry, D. J. F. Fulgoni, P. J. Phillips, T. E. Whall,
E. H. C. Parker, and P. G. Coleman

JOURNAL OF APPLIED PHYSICS
VOLUME 89, NUMBER 1
1 JANUARY 2001
Porosity in low dielectric constant SiOCH films depth profiled by positron annihilation spectroscopy
R. S. Brusa, M. Spagolla, G. P. Karwasz, A. Zecca, G. Ottaviani, F. Corni, M. Bacchetta, and E. Carollo
JOURNAL OF APPLIED PHYSICS
VOLUME 95, NUMBER 5
1 MARCH 2004

(b)

as-produced or annealed samples

as-produced (500°C) (600°C) (700°C) (800°C) (900°C)

H₂ O₂ H₂O

samples aged in air (720 h)

positron implantation energy [keV]

time [h]

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CASE STUDY – SILICON WAVEGUIDE DETECTORS

- Deep-level engineering (DLE) takes advantage of the ability of ion implantation to introduce bandgap states either structurally (e.g., point defects) or through chemical doping
- DLE provides another ‘dimension’ in the design of silicon photonic circuits
- DLE was developed through a background of the study of defects and deep-levels and the use of ion implantation for doping and in particular implantation isolation of GaAs.

A nano-void imaged at McMaster using TEM – used for RI engineering and formed via He\(^+\) implantation and annealing.
**Benefit of being small**

![Diagram of diode structure with labels for TiN-Al contact pads, W plug, LPCVD SiO₂, Si wing, thermal SiO₂, waveguide, intrinsic Si, and ion damage.]

Photo current with 1 mW of 1539 nm

Power Response $S_{21}^2$ (dB)

- **Activated**
- **Not activated**

Fourier transform of pulse response

Network analyzer

0.25 mm diode, 20 V bias

- Frequency (GHz)
- Power Response $S_{21}^2$ (dB)

0.01
0.1
1
10
100

- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
- 90
- 100

- 0.5 ±0.1 A W⁻¹
- 5 V
- 5.0 ± 1 A W⁻¹
- 20 V

Benefit of being small

Slides courtesy of Mike Geis MIT Lincoln Labs

M.W. Geis et. al., Optics Express 15, 16886 (2007).
DLE detection at 2-2.5um

- Significant effort is being expended on extending the wavelength range of optical communications

- Specifically, Thulium-Doped-Fiber-Amplifiers (TDFA) are now available for operation ~2um.

- DLE has no hard wavelength cut-off (unlike Ge for instance), and we recently demonstrated that DLE can be used at extended wavelengths.

\[ \text{Ackert et al. Nature Photonics (2015)} \]
**DLE detection at 2-2.5um**

- The detectors operate error free at 20Gbps.
- Good eye diagrams observed at 28Gbps.
- 3dB bandwidth is ~15GHz.

*Physics World May 2015*

BENCH-TOP POSITRON BEAM

- We succeeded in developing a benchtop positron beam
- We modelled the footprint on previously adopted tools
- How could this fail to be adopted widely?
REACTOR-BASED POSITRON BEAM

- Canada is soon to possess one of three reactor based, slow-positron beams.
- The current radioactive source experiments will benefit from a brightness enhancement of 3 orders of magnitude.
- The experimental chamber is designed to probe semiconductors (defects and fields).
The four spectra represent 3 samples implanted with He+ ions at 500eV to dose of 1e16cm⁻²; plus an unimplanted sample.

Three implants performed at RT (red); 250C (black) and 450C (open).

A thin (10nm) highly defective layer forms at RT.

A defect layer (∼10¹⁸cm⁻³) ~80nm thick forms at 250C.

No difference between virgin and 450C (lower limit defect concentration of 1e¹⁵cm⁻³).
IN-SITU IMPLANTATION

- A unique feature of the positron beam is the integration of an ion source.
- This permits in-situ implantation and analysis of defects.

- Spectra of virgin Si; sub-amorphous implantation and amorphizing implantation (10keV Ar⁺)
Coupled with a closed cycle He cold finger, we are able to implant damage at 30k and observe annealing.

We have developed dynamic study of defects: so-called positron-DLTS which probes the electronic trapping properties of vacancy-type defects.