Multiwavelength Raman and PL Spectroscopy: Promising In-Line Diagnostic Metrology for 20nm Technology Node and Beyond

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Outline

• Importance of Diagnostic Metrology
  • Requirements
    • Non-invasive (non-destructive, preferentially non-contact)
    • No sample preparation
    • Fast measurement and analysis (for in-line monitoring)
    • Blanket and pattern wafer characterization capability
    • Access to material property information

• Diagnostic Metrology Technology and Products from WaferMasters

• Interactions between Light and Semiconductors
  • Scattering
    • Elastic scattering (Rayleigh scattering or reflection)
    • Inelastic scattering (Raman scattering) → Raman Spectroscopy
  • Photoluminescence → PL Spectroscopy

• Application Examples (Si, SiGe, Si:C, Ge, Ge/Si, III-V/Si, TSVs etc.)
  • Stress, strain, defects, damages
  • Composition
  • Contamination
Importance of Diagnostic Metrology

- **Device Dimension Shrinkage**
  - Continuous Shrinkage of Lg
  - 45nm Node: Lg <25nm
  - 16nm Node: Lg ~6nm

- **Ultra-Shallow Junction**
  - Ultra-Shallow Junction Depth
  - High Dopant Concentration

- **Strain Engineering**
  - SiGe, Si:C

- **New Device Structures**
  - Non-planar CMOS
  - FINFET

- **Introduction of New Materials**
  - High k, Low k Dielectrics
  - Metal Gate
  - New Silicides
  - SOI
  - III-V Compound Semiconductor Alloys
  - CNT, Graphene

- **Process Window Narrowing**
  - Tight Process Control
  - Process Uniformity
  - Process Repeatability
  - Tool Matching
  → **In-Line Monitoring**
  → **Fast Feedback**
  → **Corrective Actions**
Importance of Diagnostic Metrology

- **Wafer Starts**
  - Sampling
  - Destructive Test

- **Process Step A**
  - Destructive Test

- **Process Step B**
  - Destructive Test

- **Process Step C**
  - Destructive Test

- **Process Step D**
  - Destructive Test

- **Process Step E**
  - Destructive Test

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- **Wafer Starts**
  - Sampling
  - In-Line Metrology

- **Process Step A**
  - In-Line Metrology

- **Process Step B**
  - In-Line Metrology

- **Process Step C**
  - In-Line Metrology

- **Process Step D**
  - In-Line Metrology

- **Process Step E**
  - In-Line Metrology

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- **Final Devices**
- **Final Devices**

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- **No Wafer Loss**
- Tracing of identical wafer
- Fast feedback

- **Wafer Loss**
- Relying on sampling and statistics
- Slow feedback
WaferMasters determined that the industry lacked tools to evaluate the characteristic lattice damage, defects and conductivity impairment inadvertently caused by process tools. The physics of optimum **Raman Spectroscopy (MRS-300)**, **Optical Surface Profiling (OSP-300)** and **Photoluminescence (MPL-300)** Platforms were researched to provide the accuracy, stability and performance required to be useful in non-destructive in-line process monitoring, optimization and control.
OSP-300: Optical Surface Profilometry is an accurate direct measurement technology for mapping the wafer surface, showing local maxima, minima and shape changes due to global and local distortion with process sequence. Often this data can be correlated to stress changes, pattern overlay and wafer breakage problems along process steps.
Interaction between Light and Semiconductors

Rayleigh Scattering (Elastic Scattering): $h\nu$ 
→ No energy change (No interest)

Raman Scattering (Inelastic Scattering): $h\nu \pm \omega_0$
→ Slight energy change by lattice vibration
→ Physical or mechanical information
  stress, strain, composition, crystallinity, damage, dopant, grain size, silicides etc.

Photoluminescence: $\sim E_g$
→ Electronic structural information
  bandgap, impurity levels and defect states, carrier concentration, dopant activation, electrically active damage/contamination, electronic complexes (excitons) and relaxation mechanisms of carriers

Excitation Light Source UV-VIS-NIR Laser

To Camera
→ Scattered Light & Luminescent Light

To Spectrometer via designed optical paths

Wafer Stage

Objective Lens

Probing depth

Wavelength
Short → Long

Si
MRS-300: Multi-wavelength Raman Spectroscopy allows depth profiling of lattice stress characteristics, dopant activation, implant species concentration, and other process parameters with great measurement stability. This technology is being applied to new challenges in Si stress characterization in advanced devices and TSV structures. Ge content uniformity and SiGe layer thickness monitoring of SiGe/Si has become an exciting application in the last few years.
Multi-wavelength Raman Spectroscopy

Monochromatic Light Excitation

\[ h\nu \]

Rayleigh Scattering or Elastic Scattering

No Wavelength Change

Inelastic Scattering

Wavelength Change by Lattice Vibration Energy \( \omega_0 \)

Probability: <1ppm

\[ \omega^2 = k \]

Monochromatic Light Scattering

\[ h\nu \]

Raman Scattering

\[ h\nu - \omega_0 \]
Multi-wavelength Raman Spectroscopy

MRS-300: Multiwavelength → Raman Spectra → Depth Profiling, Surface Damage
Raman Shift → Material Identification (Si, SiGe, III-V etc.)
FWHM → Crystal Orientation
Asymmetry → Stress, Crystallinity
Intensity → Defects, Grain Size Distribution, Crystallinity

Ge Content

SiGe Thickness

Normalized Intensity

Peak Shift

Broadening

Asymmetry ($\Gamma_a/\Gamma_b$)

Raman Shift

Ge Content Uniformity

Si$_x$Ge$_{1-x}$ Thickness Uniformity
MPL-300: Multiwavelength Photoluminescence Spectroscopy. The most direct way to measure band-gap energies, dopant activation, electrically active defects, metal contamination which affect minority carrier lifetime and electron mobility characteristics of the semiconductor.
**Multiwavelength Photoluminescence Spectroscopy**

**MPL-300:** Multiwavelength → Depth Profiling, Passivation, Interface Quality
   PL Intensity → Electrically Active Dopants, Defects, II Damage, Contamination, Minority Carrier Lifetime

   PL Peak Position → Bandgap, Dopant Concentration
   PL Spectral Response → Defects, II Damage, Dopant, Crystallinity

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**PL Maps of 300mm Prime Si Wafer**

- **532 nm Excitation**
  - Peak Wavelength (nm)
  - FWHM (nm)
  - PL Intensity (Counts)

- **650 nm Excitation**
  - Peak Wavelength (nm)
  - FWHM (nm)
  - PL Intensity (Counts)

- **827 nm Excitation**
  - Peak Wavelength (nm)
  - FWHM (nm)
  - PL Intensity (Counts)
PL Intensity Patterns and Their Interpretation

- Poor Passivation and/or Surface Damage
- Subsurface Defects and/or Implant EOR Damage
- Poor Passivation and/or Dopant Variations
- Poor Passivation and/or Poor Crystallinity and/or Heavy Doping

Intensity vs. Wavelength:
- 515nm: 2.41eV
- 650nm: 1.50eV
- 827nm: 1.50eV

Depth Indicators:
- ~1.3μm
- ~4.0μm
- ~10.0μm

Interpretation:
- Poor Passivation: Reduced intensity at lower wavelengths.
- Subsurface Defects: Enhanced intensity at higher wavelengths.
- Dopant Variations: Consistent intensity patterns across wavelengths.
- Poor Crystallinity: Fluctuating intensity patterns.
- Heavy Doping: Increased intensity at specific wavelengths.
Effect of Substrate and Process on PL Intensity

**Process Dependence**

- Implant + RTA at 1100°C
- p/p+ Epilayer
- 2hr Furnace Anneal in Ar
- p/p- Epilayer
- RTA in Ar Pure Si
- Reference Ar Pure Si

**PL Intensity Maps**

- Failed DRAM: Lower Intensity
- Normal DRAM: Higher Intensity
Raman and PL Characterization Example: USJ

0013-4651/2010/158(1)/H80/5/$28.00 © The Electrochemical Society

Non-Contact and Non-Destructive Characterization
Alternatives of Ultra-Shallow Implanted Silicon p-n Junctions
by Multi-Wavelength Raman and Photoluminescence Spectroscopy

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Excitation Wavelength (nm) vs. Probing Depth (nm)

Excitation Wavelength (nm) vs. Probing Depth (μm)

B+ 1keV 1.0x10^15 cm^-2

Sheet Resistance (Ohm/sq)

Annealing Temperature (°C)

B Concentration (cm^-3)

Depth (nm)

As implanted
850°C, 100s
900°C, 100s
950°C, 100s
1000°C, 100s
Raman and PL Study: USJ

**Raman**

- **Intensity** (arbitrary units)
  - 363.8 nm
  - 457.9 nm
  - 488.0 nm
  - 514.5 nm

**PL**

- **Wavelength (nm)**
  - 515 nm
  - 650 nm
  - 827 nm

**UV Raman**

- **FWHM (cm⁻¹)**

**VIS Raman**

- **PL from Band Edge**
  - 363.8 nm
  - 457.9 nm
  - 488.0 nm
  - 514.5 nm

**Long λ PL**

- **PL intensity (Counts)**

**Short λ PL**

- **Sheet Resistance (ohm/sq.)**
Raman Characterization Example: Implanted Si

B 5keV 3E15cm⁻²

As Implanted

Depth (nm)

B Concentration (atoms/cm³)

1.0E+22
1.0E+21
1.0E+20
1.0E+19
1.0E+18
1.0E+17
1.0E+16

0
200
400
600
800

457.9nm
488.0nm
514.5nm

~290nm
~490nm
~645nm

Bulk Si

Raman Shift (cm⁻¹)

FWHM (cm⁻¹)

As Implanted

1050°C, 240s
1050°C, 300s
1050°C, 360s
1100°C, 240s
1100°C, 300s
1100°C, 360s

Shift
FWHM

457.9nm
488.0nm
514.5nm

~290nm
~490nm
~645nm

Bulk Si

Raman Shift (cm⁻¹)

FWHM (cm⁻¹)

As Implanted

1050°C, 240s
1050°C, 300s
1050°C, 360s
1100°C, 240s
1100°C, 300s
1100°C, 360s

Shift
FWHM

457.9nm
488.0nm
514.5nm

~290nm
~490nm
~645nm

Bulk Si

Raman Shift (cm⁻¹)

FWHM (cm⁻¹)

As Implanted

1050°C, 240s
1050°C, 300s
1050°C, 360s
1100°C, 240s
1100°C, 300s
1100°C, 360s

Shift
FWHM

457.9nm
488.0nm
514.5nm

~290nm
~490nm
~645nm

Bulk Si
PL Characterization Example

B 5keV 3E15cm$^{-2}$

Annealing Temp. Dependence

Annealing Time Dependence

827.0 nm

As Implanted

1100°C, 90s
1050°C, 90s
1000°C, 90s
950°C, 90s
900°C, 90s

900°C~1100°C
30s~360s

827.0 nm

900°C, 180s
1000°C, 90s
1000°C, 60s
1000°C, 45s
1000°C, 30s
As Implanted
Raman and PL Characterization Example: Si:C

Compressive

Tensile

363.8nm

441.6nm

457.9nm

488.0nm

514.5nm

Si

as-grown

after anneal

532nm

650nm

827nm

Intensity (Counts)

Intensity (Counts)

Wavelength (nm)

Wavelength (nm)
Raman and PL Characterization Example: Si:C

**Raman Shift (cm⁻¹)**

- 490
- 495
- 500
- 505
- 510
- 515
- 520
- 525
- 530
- 535

**Intensity (arb. units)**

- 363.8nm
- 441.6nm
- 457.9nm
- 488.0nm
- 514.5nm

**Wavelength (nm)**

- 532nm
- 650nm
- 827nm

**Intensity (Counts)**

- 0
- 5000
- 10000
- 15000
- 20000
- 25000
- 30000
- 35000
- 40000

**Wavelength (nm)**

- 900
- 1000
- 1100
- 1200
- 1300
- 1400

**Intensity (Counts)**

- 0
- 5000
- 10000
- 15000
- 20000
- 25000
- 30000
- 35000
- 40000

**WaferMasters Incorporated**
Raman Characterization Example: Flash Memory

Design of Multi-Wavelength Micro Raman Spectroscopy System and Its Semiconductor Stress Depth Profiling Applications

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Advanced Flash Memory Chip
Raman Characterization Example: Cu TSV

Three Dimensional Stress Mapping of Silicon Surrounded by Copper Filled through Silicon Vias Using Polychromator-Based Multi-Wavelength Micro Raman Spectroscopy

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**Stress**

- **Before Anneal**: Compressive
- **After Anneal**: Compressive

**3μm Cu Filled TSVs**

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Raman Characterization Example: Cu TSV

Stress evolution in surrounding silicon of Cu-filled through-silicon via undergoing thermal annealing by multiwavelength micro-Raman spectroscopy

W.S. Kwon et al.
Fig. 2 – Raman spectra from a metallic (top) and a semiconducting (bottom) SWNT at the single nanotube level using 785 nm (1.58 eV) laser excitation, showing the radial breathing mode (RBM), D-band, G-band, and $G'$ band features, in addition to weak double resonance features associated with the M-band and the iTOLA second-order modes. Insets on the left and the right show, respectively, the atomic displacements associated with the RBM and G-band normal mode vibrations. The isolated carbon nanotubes are siting on an oxidized silicon substrate which provides contributions to the Raman spectra denoted by $**$ which are used for calibration purposes.

**Custom Design Diagnostic Metrology Products**

**Raman:**
- Wavelengths: UV-VIS-NIR (Option)
- Beam Size: 0.5~2.0µm
- Resolution: High, Medium, Low
- Sample Size: Piece to 300mm Wafer
- Measurement Time: s~min/point
- Automation: Full Automation, Pattern Recognition

**PL:**
- Ext. Wavelengths: VIS-NIR (Option)
- Beam Size: 10~200µm
- Spectral $\lambda$ Range: VIS- NIR (Option)
- Temperature: RT or Cryogenic
- Resolution: High, Medium, Low
- Sample Size: Piece to 300mm Wafer (RT)
  - Piece (Cryogenic)
- Measurement Time: ms~s/point
- Automation: Full Automation, Pattern Recognition

**Custom Design and Consultation Services:**
Custom design and consultation services are available in wide range of semiconductor process and material characterization.
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