Photoluminescence Intensity Technique for Oxide-Semiconductor Interface Characterization

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PL-Intensity: Outline

Introduction
  • History & Rationale
  • Physics: Capture/emission vs. recombination

Experimental Implementation
  • Experimental setup
  • Test structure design

Results
  • Interface quality screening
  • Models, $D_{it}$, $S$ and $\sigma$

Impact and Outlook
  • Instrumental in successful GaAs MOSFET development
  • Extension to small bandgap channel material
PL-Intensity: Outline

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PL-Intensity: History and Rationale

Originally developed for dielectrics on GaAs
  • Early developments at Bell Labs and Hokkaido University
  • Experimental setup in final form in Motorola in 1996
  • Model for $D_{it}$ extraction on GaAs since 1998

Difficulty to interpret capture/emission data (e.g. C-V, G-V) on wider bandgap semiconductors
  • Very long capture/emission time constants (100 s) at GaAs midgap at room temperature (RT)
  • Midgap Fermi level pinning is single dominant issue on GaAs but is not detectable in RT ac measurements
  • Under steady-state deep depletion, traps are not observable at the capacitors terminals
  • Dielectric leakage currents interfere with capture/emission data

Advantages
  • Not afflicted with ambiguities of capture/emission data
  • Works for dielectric of any thickness and only requires minor band offsets for carrier confinement
  • Requires no device manufacturing (perfect for screening)
PL-Intensity: Physics

Carrier Capture/Emission $\tau$

- $\tau$ is exponential function of $E_T$
- Interface state density $D_{it} = f (E_T)$
**PL-Intensity: Physics**

### Carrier Capture/Emission $\tau$

- $\tau$ is exponential function of $E_T$
- Interface state density $D_{it} = f(E_T)$

### Carrier Recombination $\tau_{n/p}$

- $\tau_{n/p} \neq f$ (trap energy $E_T$)
- $D_{it}$ integrated over bandgap

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Dielectric

Semiconductor

- Admittance - (Capacitance/Conductance)
- Voltage

Active Layer 1.5 $\mu$m

- Photoluminescence Intensity

Active Layer

- Trap

Electrical

$E_c$

$E_F$

$E_v$

$I_0'$

$I_{PL}$

$I_{rad}$

$E_{F_n}$

$E_{F_p}$

Buffer (0.2 $\mu$m)

Buffer (0.2 $\mu$m)

- Trap

- Interface state density $D_{it}$
PL-Intensity: Physics

Laser Excitation of Intensity $I_0$

Photoluminescence of Intensity $I_{PL}$

$\eta = \frac{I_{PL}}{I_0} \Rightarrow N_{it} (D_{it} \text{ integrated over bandgap})$

Carrier Lifetime $\tau_{n/p} = \frac{1}{\sigma v_{th} N_{it}} \neq f(E_T, n_i)$

Unique Tool to Screen Interfaces for Device Quality
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PL-Intensity: Experimental Implementation

1996: Analysis of Electrical Interface Properties

- Laser
- Microscope
- Spectrometer
- CCD
- Probe Stage
- Telescope
- ND Filter
- Wheels
- Precision Aligned Optics

Photoluminescence Intensity
PL-Intensity: Experimental Implementation

Parameter:
Laser Power Density $P_0'$
$7 \times 10^3$, $7 \times 10^1$, $8 \times 10^{-1}$ W/cm$^2$

Spectra integrated over wavelength for $I_{PL}$ vs. $P_0'$ plots
PL-Intensity: Test Structure Design

n⁻ GaAs Active Layer (1.5 µm): \( \tau_{\text{epi}} (\approx 100 \text{ ns}), \tau_{\text{rad}} \)

n⁺ GaAs Buffer (0.2 µm): \( \tau_{\text{epi}} \)

Undoped Alₐ₀.₄₅Ga₀.₅₅As (0.1 µm): \( \Delta E_c, \Delta E_v \)

n⁺ GaAs Buffer (0.2 µm): \( \tau_{\text{epi}} \)

n⁺ GaAs Substrate: \( \tau_{\text{sub}} (\approx 10\text{ns}) \)

Interface to be characterized

\( \tau_{\text{int}}, Q_{\text{int}} \Rightarrow N_{\text{it}} (D_{\text{it}}) \)

100% of photons are absorbed
Low doping for good \( \tau_{\text{int}}, Q_{\text{int}} \) resolution

High n⁺ doping screens AlGaAs/GaAs backside interface

AlGaAs layer screens substrate and substrate/epi interface effects (recombination) and confines generated carriers to active layer

n⁺ GaAs buffer layer provides flatband condition
Substrate/epi \( \tau_{\text{int}}, Q_{\text{int}} \)

Also suitable for capture/emission (C-V, G-V) analysis
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PL-Intensity: Interface Quality Screening

Normalized Photoluminescence Intensity (arb. units)

MBE Grown GaAs Surface

Excitation Intensity (W/cm²)

10^7
10^6
10^5
10^4
10^3
10^2
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
PL-Intensity: Interface Quality Screening

Normalized Photoluminescence Intensity (arb. units) vs Excitation Intensity (W/cm²)

MBE Grown GaAs Surface

AlGaAs

Known Best Interface: AlGaAs/GaAs

Known Worst Interface: Native Oxide/GaAs
PL-Intensity: Interface Quality Screening

Normalized Photoluminescence Intensity (arb. units) vs. Excitation Intensity (W/cm²)

- MBE Grown GaAs Surface
  - AlGaAs

- Oxides, Nitrides on GaAs: Native Oxide Behavior

- Known Best Interface: AlGaAs/GaAs

- Known Worst Interface: Native Oxide/GaAs
PL-Intensity: Interface Quality Screening

**Known Best Interface:**
AlGaAs/GaAs

**Device Quality Interface:**
Ga$_2$O$_3$/GaAs

**Oxides, Nitrides on GaAs:**
Native Oxide Behavior

**Known Worst Interface:**
Native Oxide/GaAs

**Normalized Photoluminescence Intensity (arb. units)**

**Excitation Intensity (W/cm$^2$)**

- MBE Grown GaAs Surface
- AlGaAs
- Ga$_2$O$_3$
- Native Oxide

- as-dep.
**PL-Intensity: Interface Quality Screening**

- **Known Best Interface:** AlGaAs/GaAs
- **Device Quality Interface:** Ga$_2$O$_3$/GaAs
- **Oxides, Nitrides on GaAs:** Native Oxide Behavior
- **Known Worst Interface:** Native Oxide/GaAs

**Graph:**
- **MBE Grown GaAs Surface**
- **AlGaAs**
  - H-passivated
  - as-dep.
- **Ga$_2$O$_3$**
  - as-dep.
- **Native Oxide**

**Axes:**
- **Normalized Photoluminescence Intensity (arb. units)**
- **Excitation Intensity (W/cm$^2$)**
**PL-Intensity: Interface Quality Screening**

![Graph showing PL intensity vs. excitation power density for different materials.](image)

- **Normalized Photoluminescence Intensity (arb. units)**
- **Excitation Power Density \( P_0' \) (W/cm\(^2\))**

- Materials: GaAs, AlGaAs, H-passivated, Bulk \( \text{Ga}_2\text{O}_3 \), \( \text{GdGaO}_3/\text{Ga}_2\text{O}_3 \), \( \text{LaAlO}_3/\text{Ga}_2\text{O}_3 \), Native Oxide, \( \text{GdScO}_3/\text{Ga}_2\text{O}_3 \), \( \text{LaAlO}_3 \), \( \text{GdScO}_3 \).
PL-Intensity: Interface Quality Screening

- Normalized Photoluminescence Intensity (arb. units)
- Excitation Power Density $P_0'$ (W/cm$^2$)

- GaAs
- AlGaAs
- H-passivated
- Bulk Ga$_2$O$_3$
- Native Oxide
- Al$_2$O$_3$ (ALD)
- Al$_2$O$_3$ (e-beam)
- as-dep
## PL-Intensity: Interface Quality Screening

<table>
<thead>
<tr>
<th>Dielectric on GaAs</th>
<th>Technique</th>
<th>Device quality</th>
<th>Not device quality</th>
<th>Native Oxide</th>
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<tbody>
<tr>
<td>Ga$_2$O$_3$</td>
<td>effusion, e-beam</td>
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<tr>
<td>GdScO$_3$</td>
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* ex-situ
Internal Quantum Efficiency $\eta$ vs. Excitation Power Density $P_0'$ (W/cm$^2$)

- **AlGaAs/GaAs**
- **H Passivated Ga$_2$O$_3$/GaAs**
- **As deposited Ga$_2$O$_3$ on GaAs**
- **Air Exposed GaAs**

Midgap $D_{it} = 1.1 \times 10^{11}$ cm$^{-2}$ eV$^{-1}$

Midgap $D_{it} = 2.7 \times 10^{11}$ cm$^{-2}$ eV$^{-1}$

Symbols:
- Measured
- Simulated

Lines:
- Simulated (1d numerical drift-diffusion, also provides S and $\sigma$)

**PL-Intensity: Models Dit, S, $\sigma$**
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PL-Intensity: Impact and Outlook

Instrumental in successful development of GaAs MOSFET

- Enhancement mode NMOS ($V_t > 0$ V)
- Subthreshold swing 65 and 70 mV/dec for $L_g = 1$ and 0.1 $\mu$m
- $g_m$ identical to ideal model ($D_{it} = 0$) predictions

Extension to small bandgap materials (InGaAs)

- Short- and mid-wavelength infrared (up to 3.5 $\mu$m)
- Detectors are expensive
- Optical instrumentation more problematic
- InGaAs lattice matched to InP ($\lambda = 1.68$ $\mu$m) done at IMEC
- $\text{In}_{0.2}\text{Ga}_{0.8}$As quantum well structure done at Bell Labs (1994)

Extension to quantum well structures

- Problematic because of additional nonradiative recombination sources at semiconductor/semiconductor interfaces
- Problematic because many design criteria shown on slide 11 cannot be met
- It is more practical to characterize dielectric/semiconductor interfaces on thicker layers when using PL-I
Further Reading

M. Passlack et al., "Insulator passivation of In_{0.2}Ga_{0.8}As-GaAs surface quantum wells," IEEE J. of Quantum Electronics, vol. 34, no. 2, pp. 307-310, 1998.
R.J.W. Hill et al., "Enhancement-mode GaAs MOSFETs with In_{0.3}Ga_{0.7}As channel, mobility over 5000 cm2/Vs and transconductance over 475 µS/µm," IEEE Electron. Dev. Lett., vol. 28, no. 12, pp. 1080-1082, 2007.