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2012 38th IEEE Photovoltaic Specialists Conference

(PVSC 2012)

**Austin, Texas, USA
3 - 8 June 2012**

Pages 1-627



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AREA 1 PROGRAM SUMMARY

Monday, June 4

Fundamentals and New Concepts: Plenary

9:30 - 10:00 AM (Blrm D)

Fundamentals and New Concepts: Session 1 (Posters)

1:30 - 3:00 PM (EH4-A)

Fundamentals and New Concepts: Intermediate-Band

Solar Cells (Orals)

3:30 - 5:00 PM (18AB)

Tuesday, June 5

Fundamentals and New Concepts: Session 2 (Posters)

10:30 - 12:00 PM (EH4-A)

Fundamentals and New Concepts: Quantum Well Solar

Cells (Orals)

1:30 - 3:00 PM (18AB)

Fundamentals and New Concepts: Light Concentration

and Light Trapping 1 (Orals)

3:30 - 5:00 PM (18AB)

Wednesday, June 6

Fundamentals and New Concepts: Simulation and

Modeling of Advanced Concept Solar Cells (Orals)

10:30 - 12:00 PM (18AB)

Fundamentals and New Concepts: Quantum Dot Solar

Cells (Orals)

1:30 - 3:00 PM (18AB)

SCREAM Workshop

3:00 - 4:00 PM (19B)

Fundamentals and New Concepts: Session 3 (Posters)

3:30 - 5:00 PM (EH4-A)

Thursday, June 7

Fundamentals and New Concepts: Session 4 (Posters)

10:30 - 12:00 PM (EH4-A)

Fundamentals and New Concepts: Advanced

Approaches for Photoconversion (Orals)

1:30 - 3:00 PM (18AB)

Fundamentals and New Concepts: Novel Materials 1

(Orals)

3:30 - 5:00 PM (18AB)

Friday, June 8

Fundamentals and New Concepts: Novel Materials 2

(Orals)

8:30 - 10:00 AM (18AB)

Fundamentals and New Concepts: Light Concentration

and Light Trapping 2 (Orals)

10:30 - 12:00 PM (18AB)

AREA 2 PROGRAM SUMMARY

Monday, June 4

Polycrystalline Thin Films: Absorber Formation and Characterization 1 (Posters)
1:30 - 3:00 PM (EH4-B)

Polycrystalline Thin Films: Wide Bandgap Devices (Orals)
3:30 - 5:00 PM (18CD)

Tuesday, June 5

Polycrystalline Thin Films: Device Properties, Modeling, Stability, and Defect Characterization (Posters)
10:30 - 12:00 PM (EH4-B)

Polycrystalline Thin Films: Absorber and Device Modeling (Orals)
1:30 - 3:00 PM (18CD)

Polycrystalline Thin Films: Junctions and Device Stability (Orals)
3:30 - 5:00 PM (18CD)

Wednesday, June 6

Polycrystalline Thin Films: Window Layers and Flexible Devices (Orals)
10:30 - 12:00 PM (18CD)

Polycrystalline Thin Films: Thin-Film Manufacturing (Orals)
1:30 - 3:00 PM (18CD)

Polycrystalline Thin Films: Alternate Substrates, Back Contact Materials, Buffer Compounds, TCOs, Manufacturing, Metrology, Process Control, and Reliability (Posters)
3:30 - 5:00 PM (EH4-B)

Thursday, June 7

Polycrystalline Thin Films: Plenary
8:30 - 9:00 AM (Blrm D)

Polycrystalline Thin Films: Absorber Formation and Characterization 2 (Posters)
10:30 - 12:00 PM (EH4-B)

Polycrystalline Thin Films: Kesterites (Orals)
1:30 - 3:00 PM (18CD)

Polycrystalline Thin Films: CIGS Absorber Processing (Orals)
3:30 - 5:00 PM (18CD)

Friday, June 8

Polycrystalline Thin Films: CdTe Processing & Devices (Orals)
8:30 - 10:00 AM (18CD)

Polycrystalline Thin Films: CIGS Processing & Devices (Orals)
10:30 - 12:00 PM (18CD)

AREA 3 PROGRAM SUMMARY

Tuesday, June 5

III-V's and Concentrators: Cells, Modules, and
Systems 1 (Posters)
10:30 - 12:00 PM (EH4-C)

Wednesday, June 6

III-V's and Concentrators: Plenary
9:30 - 10:00 AM (Blrm D)

III-V's and Concentrators: Cells (Orals)
10:30 - 12:00 PM (17B)

III-V's and Concentrators: Modules and Systems
(Orals)
1:30 - 3:00 PM (17B)

III-V's and Concentrators: Cells, Modules, and
Systems 2 (Posters)
3:30 - 5:00 PM (EH4-C)

Thursday, June 7

III-V's and Concentrators: High-Efficiency Cells
(Orals)
1:30 - 3:00 PM (17B)

AREA 4 PROGRAM SUMMARY

Monday, June 4

Crystalline Silicon: Fundamentals (Posters)

1:30 - 3:00 PM (EH4-C)

Crystalline Silicon: New Device Concepts (Orals)

3:30 - 5:00 PM (Blrm G)

Tuesday, June 5

Crystalline Silicon: Plenary

8:30 - 9:00 AM (Blrm D)

Crystalline Silicon: Passivation and Advanced Devices
(Posters)

10:30 - 12:00 PM (EH4-D)

Crystalline Silicon: Fundamentals (Orals)

1:30 - 3:00 PM (Blrm G)

Crystalline Silicon: Advanced Devices (Orals)

3:30 - 5:00 PM (Blrm G)

Wednesday, June 6

Crystalline Silicon: Passivation (Orals)

10:30 - 12:00 PM (Blrm G)

Crystalline Silicon: Crystallization and Wafering (Orals)

1:30 - 3:00 PM (Blrm G)

Crystalline Silicon: Industrial Cell Technology (Posters)

3:30 - 5:00 PM (EH4-D)

Thursday, June 7

Crystalline Silicon: Feedstock, Crystallization, and
Wafering (Posters)

10:30 - 12:00 PM (EH4-C)

Crystalline Silicon: Texture, Emitter, and ARC (Orals)

1:30 - 3:00 PM (Blrm G)

Crystalline Silicon: Discussion and Harumph (Workshop)

3:30 - 5:00 PM (Blrm G)

Friday, June 8

Crystalline Silicon: Feedstock (Orals)

8:30 - 10:00 AM (Blrm G)

Crystalline Silicon: Metallization (Orals)

10:30 - 12:00 PM (Blrm G)

AREA 5 PROGRAM SUMMARY

Monday, June 4

Thin-Film Silicon: Solar Cells: Fundamentals,
Processing, and Light Trapping (Posters)
1:30 - 3:00 PM (EH4-D)

Thin-Film Silicon: Light Trapping in Solar Cells 1
(Orals)
3:30 - 5:00 PM (19A)

Tuesday, June 5

Thin-Film Silicon: Solar Cells, Novel Concepts, Thin
Crystalline Silicon Film, Solar Cells and Modules
(Posters)
10:30 - 12:00 PM (EH4-E)

Thin-Film Silicon: Solar Cells and Modules (Orals)
1:30 - 3:00 PM (19A)

Thin-Film Silicon: Novel Concepts: Hybrid,
Plasmonics and Diagnostic Tools (Orals)
3:30 - 5:00 PM (19A)

Wednesday, June 6

Thin-Film Silicon: Plenary
8:30 - 9:00 AM (Blrm D)

Thin-Film Silicon: Thin-Crystalline Silicon Technology
(Orals)
1:30 - 3:00 PM (19A)

Thursday, June 7

Thin-Film Silicon: Light Trapping in Solar Cells 2
(Orals)
1:30 - 3:00 PM (19A)

Thin-Film Silicon: Fundamentals and Defects in Solar
Cells (Orals)
3:30 - 5:00 PM (19A)

AREA 6 PROGRAM SUMMARY

Wednesday, June 6

Organic Photovoltaics: Contacts and Dye Cells
(Posters)
3:30 - 5:00 PM (EH4-E)

Thursday, June 7

Organic Photovoltaics: Plenary
9:00 - 9:30 AM (Blrm D)

Organic Photovoltaics: OPV Materials and Devices
(Posters)
10:30 - 12:00 PM (EH4-D)

Organic Photovoltaics: New Organic and Interface
Materials (Orals)
1:30 - 3:00 PM (17A)

Organic Photovoltaics: Device Concepts (Orals)
3:30 - 5:00 PM (17A)

Friday, June 8

Organic Photovoltaics: Lifetime Processing and
Reliability (Orals)
8:30 - 10:00 AM (17A)

Organic Photovoltaics: OPV Modeling and Inorganic
Hybrids (Orals)
10:30 - 12:00 PM (17A)

AREA 7 PROGRAM SUMMARY

Wednesday, June 6

Space Technologies: Plenary

9:00 - 9:30 AM (Blrm D)

Thursday, June 7

Space Technologies: Space PV Technologies

(Posters)

10:30 - 12:00 PM (EH4-E)

Space Technologies: High Performance PV for Space

Applications (Orals)

3:30 - 5:00 PM (17B)

Friday, June 8

Space Technologies: Testing and Design of Space PV

Technologies (Orals)

8:30 - 10:00 AM (17B)

AREA 8 PROGRAM SUMMARY

Monday, June 4

PV Characterization: Session 1 (Posters)
1:30 - 3:00 PM (EH4-E)

PV Characterization: PV Modules: Testing and
Standards (Orals)
3:30 - 5:00 PM (17A)

Tuesday, June 5

PV Characterization: Plenary
9:00 - 9:30 AM (Blrm D)

PV Characterization: Session 2 (Posters)
10:30 - 12:00 PM (EH4-F)

PV Characterization: Challenges in Characterization
of Multijunction Devices (Orals)
1:30 - 3:00 PM (17A)

PV Characterization: Defects in PV Materials and
Solar Cells (Orals)
3:30 - 5:00 PM (17A)

Wednesday, June 6

PV Characterization: Characterization of Thin Films
(Orals)
10:30 - 12:00 PM (17A)

PV Characterization: Advanced Characterization
Methods and Instruments (Orals)
1:30 - 3:00 PM (17A)

AREA 9 PROGRAM SUMMARY

Monday, June 4

Modules and Systems: Grid-Tied Systems (Posters)
1:30 - 3:00 PM (EH4-F)

Modules and Systems: Utility Scale and High Penetration
(Orals)
3:30 - 5:00 PM (16AB)

Tuesday, June 5

Modules and Systems: Inverters, Balance-of-System
Devices, and Module Shading (Posters)
10:30 - 12:00 PM (EH4-G)

Modules and Systems: Systems Design, Control, and
Performance (Orals)
1:30 - 3:00 PM (16AB)

Modules and Systems: Inverters and Balance-of-System
Devices (Orals)
3:30 - 5:00 PM (16AB)

Wednesday, June 6

Modules and Systems: PV Reliability (Orals)
10:30 - 12:00 PM (16AB)

Modules and Systems: Module Materials, Durability, and
Performance 1 (Orals)
1:30 - 3:00 PM (16AB)

Modules and Systems: Module Materials, Durability, and
Performance (Posters)
3:30 - 5:00 PM (EH4-F)

Thursday, June 7

Modules and Systems: Plenary
9:30 - 10:00 AM (Blrm D)

Modules and Systems: Irradiance Resources, PV
Modeling, and Off-Grid Applications (Posters)
10:30 - 12:00 PM (EH4-F)

Modules and Systems: PV Performance Modeling
Collaborative (Orals)
1:30 - 3:00 PM (16AB)

Modules and Systems: Module Materials, Durability, and
Performance 2 (Orals)
3:30 - 5:00 PM (16AB)

Friday, June 8

Modules and Systems: Irradiance Resources (Orals)
8:30 - 10:00 AM (16AB)

Modules and Systems: Off-Grid Applications (Orals)
8:30 - 10:00 AM (19A)

Modules and Systems: Performance Modeling (Orals)
10:30 - 12:00 PM (16AB)

AREA 10 PROGRAM SUMMARY

Monday, June 4

PV Velocity Forum: Equipment-Related PV ESH
(Orals)

1:30 - 3:00 PM (19B)

PV Velocity Forum: Sustainability and PV EHS (Orals)
3:30 - 5:00 PM (19B)

Tuesday, June 5

PV Velocity Forum: Plenary
9:30 - 10:00 AM (Blrm D)

PV Velocity Forum: PV Executive Forum
10:30 - 12:00 PM (19B)

PV Velocity Forum: National Programs (Orals)
1:30 - 3:10 PM (19B)

PV Velocity Forum: Markets and Scalability (Orals)
3:30 - 5:00 PM (19B)

Wednesday, June 6

PV Velocity Forum: Models and Markets (Orals)
10:30 - 12:00 PM (19B)

PV Velocity Forum: Session (Posters)
3:30 - 5:00 PM (EH4-G)

MONDAY PROGRAM SUMMARY

7:00 AM	Authors' Breakfast						
	7:00 - 8:00 AM						
8:00 AM	Break						
8:30 AM							
9:00 AM	Area 9 Keynote						
9:30 AM	Area 1 Plenary						
10:00 AM	Break						
10:30 AM	Opening Keynote						
12:00 PM							
1:30 PM	P1	P2	P4	P5	P8	P9	O10
3:00 PM	Break						
3:30 PM	O1	O2	O4	O5	O8	O9	O10
5:00 PM							
5:30 PM	Exhibitor's Reception						Exhibits
	5:30 - 8:00 PM						
8:00 PM							

AREA LEGEND

	Area 1: Fundamentals and New Concepts for Future Technologies
	Area 2: Thin Film Polycrystalline Photovoltaics
	Area 3: III-V and Concentrator Technologies
	Area 4: Crystalline Silicon Photovoltaics
	Area 5: Thin Film Silicon Based PV Technologies
	Area 6: Organic Photovoltaics
	Area 7: Space Technologies
	Area 8: Characterization Methods
	Area 9: PV Modules and Terrestrial Systems
	Area 10: PV Velocity Forum

O = Oral Session

P = Poster Session

Identification of metal impurities in crystalline silicon wafers

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Abstract — Injection dependent lifetime spectroscopy (IDLS) was performed to identify the type and concentration of the defects associated with metal impurities in crystalline silicon wafers. Minority carrier lifetimes in intentionally contaminated silicon wafers using various metal concentrations were measured by a transformer-coupled, radio frequency-based photo conductance measurement tool, GLMTM2000. Lifetimes in the bulk of the silicon wafers were measured at low injection level using a square pulse cycle of light with half period > 10 milliseconds to ensure steady state photoconductance was reached. Analysis of the data using Shockley-Read-Hall theory demonstrates the ratio of capture cross-section of electrically active defect level associated with molybdenum (Mo) and copper (Cu). Concentrations (N_t) of electrically active defect states associated with Mo and Cu impurity are determined from measured bulk lifetime at low level injection, using Shockley-Read-Hall carrier concentrations (n_1 and p_1), and known activation energy levels (E_t) of the identified metal from the literature.

Index Terms — minority carrier lifetime, impurity, GLMTM2000, bulk lifetime, silicon.

I. INTRODUCTION

The Silicon photovoltaic (Si-PV) industry can suffer from poor manufacturing control of metal impurities in low cost directionally solidified or cast wafers making up > 85% of the capacity being delivered today. The capability to detect the type and concentrations of impurities in solar wafers helps to qualify vendors, identify point of contamination in the fabrication line and the possible sources of contamination. Lifetime spectroscopy (LS) is a non-destructive measurement and quick analysis technique for metal impurity characterization in silicon photovoltaic (Si-PV) cells [1]. LS determines the measured lifetime dependence on various changes in either injection level or the substrate temperature to extract defect specific parameters in the silicon wafers.

Effective minority carrier lifetime in silicon wafers is often dominated by the surface recombination velocity (SRV) [2] and as such is a poor indicator of quality of the bulk property of the crystal. In this work, the bulk minority carrier lifetime signals were measured by a newly developed photoconductance measurement tool, GLMTM2000 [3] after surface passivation.

The GLMTM2000 is a multi-parameter, transformer-coupled instrument with programmable LED array that measures radio frequency based photo conductance changes in the wafer. Fig. 2 depicts the schematic diagram of the photoconductance

instrument. GLMTM2000 has the capability to use near IR LEDs for full penetration of the wafer or a green LED array penetrating near surface [3]. The unique programmable illumination method allows simultaneous determination of transient and true steady state photoconductance measurements and the capability to control the intensity of light to access ultra-low injection levels (much less than the dopant concentration, N_{dop}).

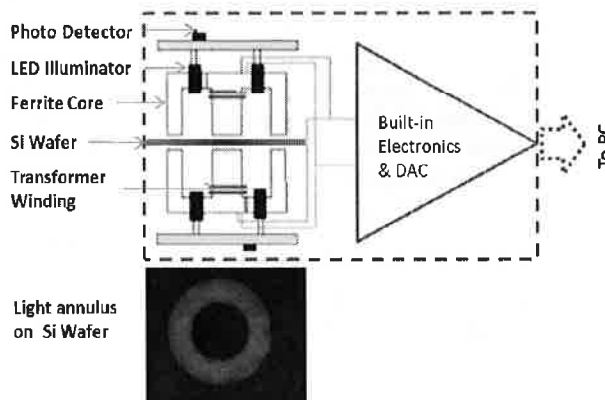


Fig 1. Schematic diagram of GLMTM2000 and light annulus on the wafer under test.

This paper explains the procedure for identification and quantification of a dominant metal impurity in silicon wafers by implementing Injection Dependent Lifetime Spectroscopy using the GLMTM2000. The theory section describes unique simplifications in applying Shockley-Read-Hall (SRH) [4, 5] lifetime expression by leveraging ultra-low level injection (LLI). In the experiment section two case studies utilizing bulk carrier lifetime measurements is described for intentionally metal-contaminated silicon wafers using Mo and Cu impurities. The measurement results, comparison to previous research, and concluding analysis are presented in the result and discussion section.

II. BACKGROUND AND THEORY

Lifetime spectroscopy is a proven technique for defect characterization in the silicon industry [1, 6] and allows for simplified instrumentation, short measurement cycles, no

sample preparation, is nondestructive, and has low cost of ownership. Alternatives for impurity identification in silicon wafers include Deep Level Transient Spectroscopy (DLTS), and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). In low level injection, $\Delta n \ll N_{D,A}$, the carrier lifetime in silicon is mostly dominated by the recombination via defect levels, otherwise known as Shockley Read Hall (SRH) [4, 5]. The well-known SRH equation shown in (1) can be simplified for the low light injection condition.

$$\tau_{SRH} \equiv \frac{\Delta n}{U_{SRH}} = \frac{\tau_{p0}(n_1 + n_0 + \Delta n) + \tau_{n0}(p_0 + p_1 + \Delta n)}{n_0 + p_0 + \Delta n} \quad (1)$$

Further simplification of the SRH equation for a p -type Si-wafer can be made when the defect energy level (E_t) lies in the lower half of the band gap (LBGH). The LBGH approximation can be made when the following assumptions hold true: (A) electron concentration at thermal equilibrium (n_0) in silicon can be neglected in comparison to the holes concentration (p_0) at room temperature ($n_0 \ll p_0$), (B) SRH electron concentrations (n_1), are sufficiently less than Δn when E_t lies in the LBGH [4, 5] and satisfies $n_1 + n_0 \ll \Delta n$ as well as for a deep levels $p_1 \ll p_0$ at room temperature, and (C) for low level injection (LLI), $p_0 \gg \Delta n$, Δn can be removed from the denominator and from the second part of the numerator in (1), which can be re-expressed as

$$\tau_{SRH}(T) = \tau_{n0}(T) + \frac{\tau_{p0}(T)}{p_0(T)} \times (\Delta n) \quad (2)$$

Hence for a particular temperature and Δn range, when conditions A, B and C are satisfied, a plot of $\tau_{SRH}(T)$ versus Δn gives a slope equals to $\tau_{p0}(T)/p_0(T)$ and an intercept as $\tau_{n0}(T)$. These measured quantities explicitly determine τ_{p0} and τ_{n0} and give a characteristic capture cross section ratio (σ_n/σ_p). This ratio uniquely establishes an impurity type and serves as a fingerprint for a metal impurity in the silicon wafer. An analogous approximation can be made at LLI for different Si-PV use cases such as; p -type Si with defect in upper half of the band gap (UBGH).

Simplified SRH equation for n -type Si, when the E_t lies in the LBGH and UBGH can be expressed as

$$\tau_{SRH}(T) \times = \tau_{p0}(T) + \frac{\tau_{n0}(T)}{n_0(T)} \times (\Delta n) \quad (3),$$

$$\tau_{SRH}(T) = \tau_{p0}(T) \left[\frac{n_1(T) + n_0(T)}{n_0(T)} \right] + \frac{\tau_{n0}(T)}{n_0(T)} \times \Delta n \quad (4)$$

SRH capture time constants for τ_{n0} and τ_{p0} can be determined using (3) with doping density n_0 and $n_1(T)$ can be calculated from the known defect energy level [7] for the temperature range as shown in Fig 2. Capture cross section ratios are calculated by using (3) and (4) and the thermal velocity for electron and holes [7] as

$$\sigma_n \equiv \frac{1}{N_t \times v_{thn} \times \tau_{n0}} \text{ and } \sigma_p \equiv \frac{1}{N_t \times v_{thp} \times \tau_{p0}} \quad (5)$$

where, N_t is the electrically active defect density and v_{thn} and v_{thp} are the thermal velocities of electrons and holes in the silicon. Hence the characteristic ratio, σ_n/σ_p of the recombination center of the defect energy level in the bulk of the silicon wafer can be calculated from the slope and intercepts of the linear fit of the minority carrier lifetime at LLI, when the E_t lies in the LBGH as

$$\frac{\sigma_n}{\sigma_p} = \frac{\text{Intercept} \times v_{thp}}{\text{Slope} \times v_{thn} \times n_0} \quad (6)$$

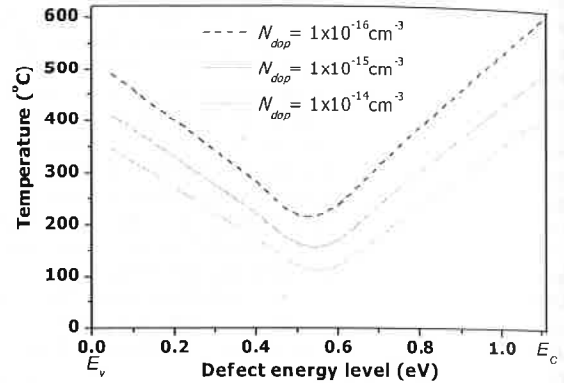


Fig 2. Minimum temperature required for $p_1(T)$ or $n_1(T) \gg 0.0001 \times p_0(T)$ or $n_0(T)$ for different N_{dop} and E_t .

The assumption $p_1(T)$ or $n_1(T) \gg 0.01 \times \Delta n$ becomes invalid as the E_t goes deeper into the band gap of Silicon and the linear fit of measured lifetime at LLI against excess carrier density no longer prevail at the room temperature. Fig 2 presents the minimum temperature required for $p_1(T)$ or $n_1(T) \gg 0.0001 \times p_0(T)$ or $n_0(T)$ for different N_{dop} and E_t .

III. EXPERIMENTS

Phosphorous-doped c-Si samples with resistivity measurements of $5 \pm 2 \Omega \text{ cm}$ ($N_{dop} \approx 9.2 \times 10^{14} \text{ cm}^{-3}$) were used. Sections ($5 \times 5 \text{ cm}^2$) were cut out of from the large-area wafers ($15.6 \times 15.6 \text{ cm}^2$) with an average width of 200 microns. The wafers were RCA cleaned before dipping into five different concentrations of metal spiked solutions at room temperature. For Mo-contaminated samples, five wafers were dipped into the spiked solutions of concentrations 0.1, 1, 10, 100, 1000 ppm followed by a drive-in annealing process, 10 hr, 1000 °C in a vertical tube furnace under Argon (Ar) ambient, followed by slow cooling in air. The wafers are labeled as Mo_1 to Mo_5. For Cu-contaminated samples, 2 wafers were dipped into the spiked solutions of 1, 10 ppm with concentrations 1 and 10 ppm followed by a drive-in annealing for 30 min at 900 °C in a similar condition as mentioned above. The wafers are labeled as Cu_1 and Cu_2.

Minority carrier lifetimes in the bulk of the metal contaminated Si-wafer and the control Si-wafer (sister wafer without metal contamination) were measured by using a transformer-coupled, radio frequency-based photo conductance (RF-PC) measurement tool, GLMTM2000, explained elsewhere [3]. An array of light emitting diodes (LEDs) of 890 nm wavelength of light were used to illuminate the silicon wafers and partially processed cells for more than 10 ms, to ensure that steady state photoconductance was achieved..

III. RESULTS AND DISCUSSIONS

The Minority carrier lifetimes in Mo-contaminated wafers were found to be less than the reference wafer by a factor of 3 to 7, which showed the Mo-defects were dominating the recombination centers. Continuous lines are the fitted SRH lifetime with Mo impurity with defect energy level $E_t = E_v + 0.31$ eV [1], $\sigma_p = 6 \times 10^{-16}$ cm² [8]. Measured injection dependent lifetime at LLI is depicted in Fig 3 (a).

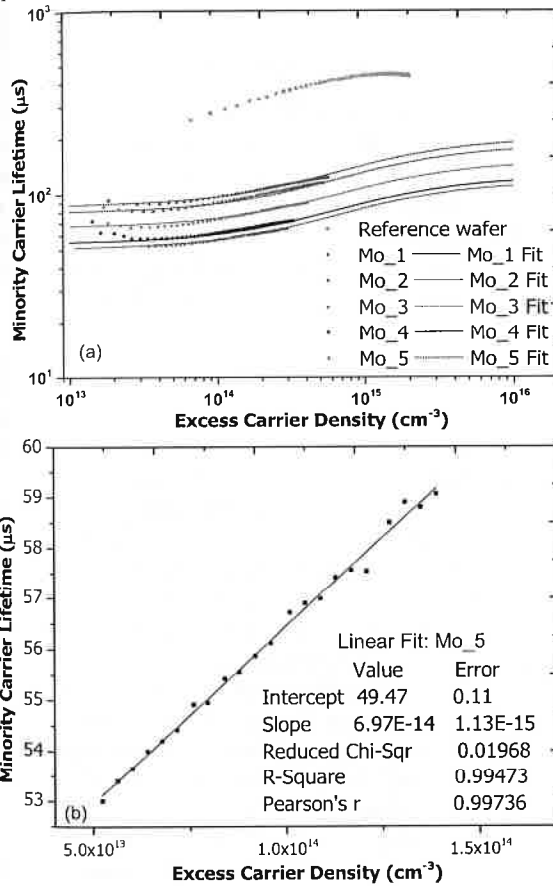


Fig 3. (a) Minority carrier lifetime measured in Mo-contaminated and reference wafer for various excess carrier densities. Continuous line shows the fitted SRH lifetime with Mo impurity. (b) Linear fit of the measured lifetime versus excess carrier density data for sample Mo_5.

The measured injection dependent minority carrier lifetimes of the Mo contaminated Si-wafers at low injection level are fitted linearly. Linear fit of the measured lifetime versus excess carrier density data for sample Mo_5 is depicted in Fig 3 (b). The characteristic ratio (σ_n/σ_p) is calculated by using (6). Measured slopes and intercepts with calculated σ_n/σ_p are depicted in Table I.

TABLE I
SUMMARY OF THE MEASURED PARAMETERS

Wafer ID	Slope(τ_{n0}/n_0)	Intercepts (τ_{p0})	(σ_n/σ_p)
Mo_1	1.25×10^{-13}	84.55	0.42 ± 0.04
Mo_2	1.11×10^{-13}	79.19	0.43 ± 0.04
Mo_3	1.02×10^{-13}	63.18	0.45 ± 0.04
Mo_4	7.56×10^{-14}	54.12	0.44 ± 0.04
Mo_5	6.97×10^{-14}	49.47	0.43 ± 0.04

The concentration of electrically active Mo-defect levels in the silicon wafers (N_t) is calculated by using the literature value $\sigma_p = 6 \times 10^{-16}$ cm² [8] and are depicted in Table II. A monotonic increment of impurity concentration on the wafers from Mo_1 to Mo_5 is expected according to the concentrations of Mo-spiked solutions during the contamination.

TABLE II
SUMMARY OF THE CALCULATED PARAMETERS

Wafer ID	N_t (cm ⁻³)	σ_n (cm ²)
Mo_1	2.55×10^{12}	2.52×10^{-16}
Mo_2	2.75×10^{12}	2.58×10^{-16}
Mo_3	3.25×10^{12}	2.70×10^{-16}
Mo_4	4.00×10^{12}	2.64×10^{-16}
Mo_5	4.32×10^{12}	2.58×10^{-16}

Measured value of capture cross section ratio is lower than the literature values [1, 8, 9]. The capture mechanism for electrons and holes of Mo defects in silicon follows the excitonic Auger capture (EAC) [10] and has a strong temperature dependent behavior. The difference in the measured results of σ_n/σ_p is obvious for the measurements taken at different temperatures.

Cu is incorporated into the silicon lattice in interstitial form, introducing one of three defect energy levels (E_t). These defect levels may appear in the form of substitutional Cu or as the Cu-related pairs. The substitutional Cu in the silicon lattice are namely, an acceptor (Cu_s^-), a donor (Cu_s^+) and a double donor (Cu_s^{++}), all of which can act as recombination centers [8, 11]. It is essential to first make sure of the dominance of a particular energy level before performing lifetime spectroscopy for defect characterization. The dominant defect is confirmed as Cu_s^- by analyzing the measured lifetime data with the procedure mentioned elsewhere [12].

The measured lifetime on Cu-contaminated were found to be less than an order of magnitude then the reference wafer, which showed the Cu-defects were dominating the recombination centers. Continuous lines are the fitted SRH lifetime with Cu_s^- impurity with defect energy level $E_t = E_C - 0.161 \text{ eV}$, $\sigma_n = 1.9 \times 10^{-17} \text{ cm}^2$ [8, 11]. Measured injection dependent lifetime at LLI is depicted in Fig 4 (a).

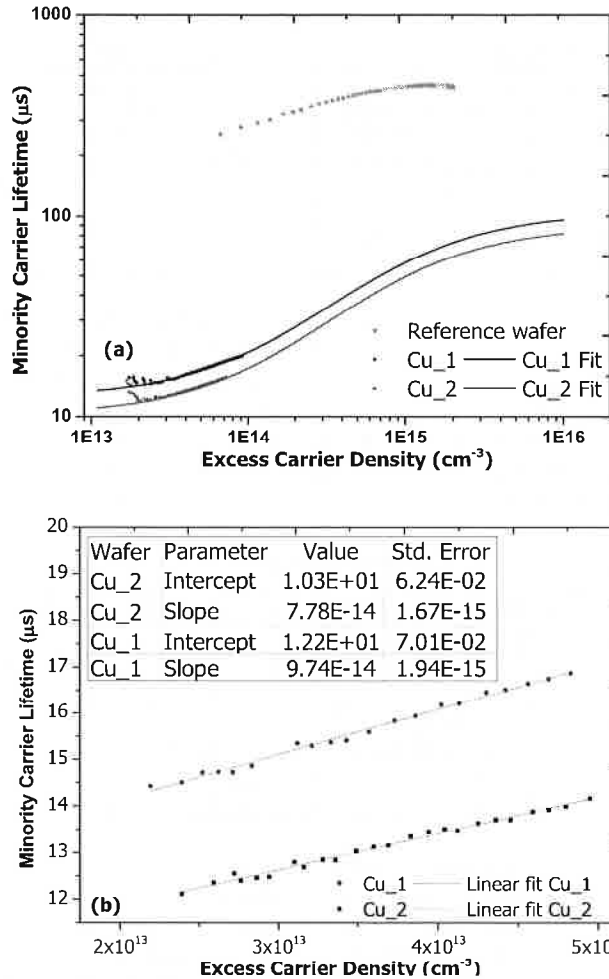


Fig 4. (a) Minority carrier lifetime measured in Cu-contaminated and reference wafer for various excess carrier densities. Continuous line shows the fitted SRH lifetime with Cu impurity (aa). (b) Linear fit of the measured lifetime versus excess carrier density.

The measured injection dependent minority carrier lifetimes of the Cu contaminated Si-wafers at low injection level are fitted linearly. Linear fit of the measured lifetime versus excess carrier density data for sample Cu_1 and Cu_2 are depicted in Fig 4 (b). The characteristic ratio (σ_n/σ_p) is calculated by using (4). Measured slopes and intercepts with calculated σ_n/σ_p are depicted in Table III.

TABLE III
SUMMARY OF THE MEASURED PARAMETERS

Wafer ID	Slope(τ_{n0}/n_0)	Intercepts (τ_{p0})	(σ_n/σ_p)
Cu_1	9.74×10^{-14}	12.18	$1/526 \pm 50$
Cu_2	7.78×10^{-14}	10.29	$1/538 \pm 50$

The concentration of electrically active Cu_s^- -defect levels in the silicon wafers (N_t) is calculated by using the literature value [8, 11] and are depicted in Table IV. Calculated impurity concentration on the sample Cu_1 and Cu_2 is consistent with the concentrations of Cu-spiked solutions during the contamination.

TABLE IV
SUMMARY OF THE CALCULATED PARAMETERS

Wafer ID	$N_t (\text{cm}^{-3})$	$\sigma_p (\text{cm}^2)$
Cu_1	4.3×10^{13}	1.02×10^{-14}
Cu_2	5.2×10^{13}	1.00×10^{-14}

IV. CONCLUSION

An explicit measurement of σ_n/σ_p was performed for Mo and Cu-contaminated wafers performed applying IDLS. Electrically active Mo_i^+ and Cu_s^- concentrations (N_t) were calculated by using the value of $\sigma_p = 6 \times 10^{-16} \text{ cm}^2$ and $\sigma_p = 1.9 \times 10^{-17} \text{ cm}^2$ respectively from the literature. Measured N_t were found in accordance with the impurity concentration on the metal spiked solution prepared for contamination.

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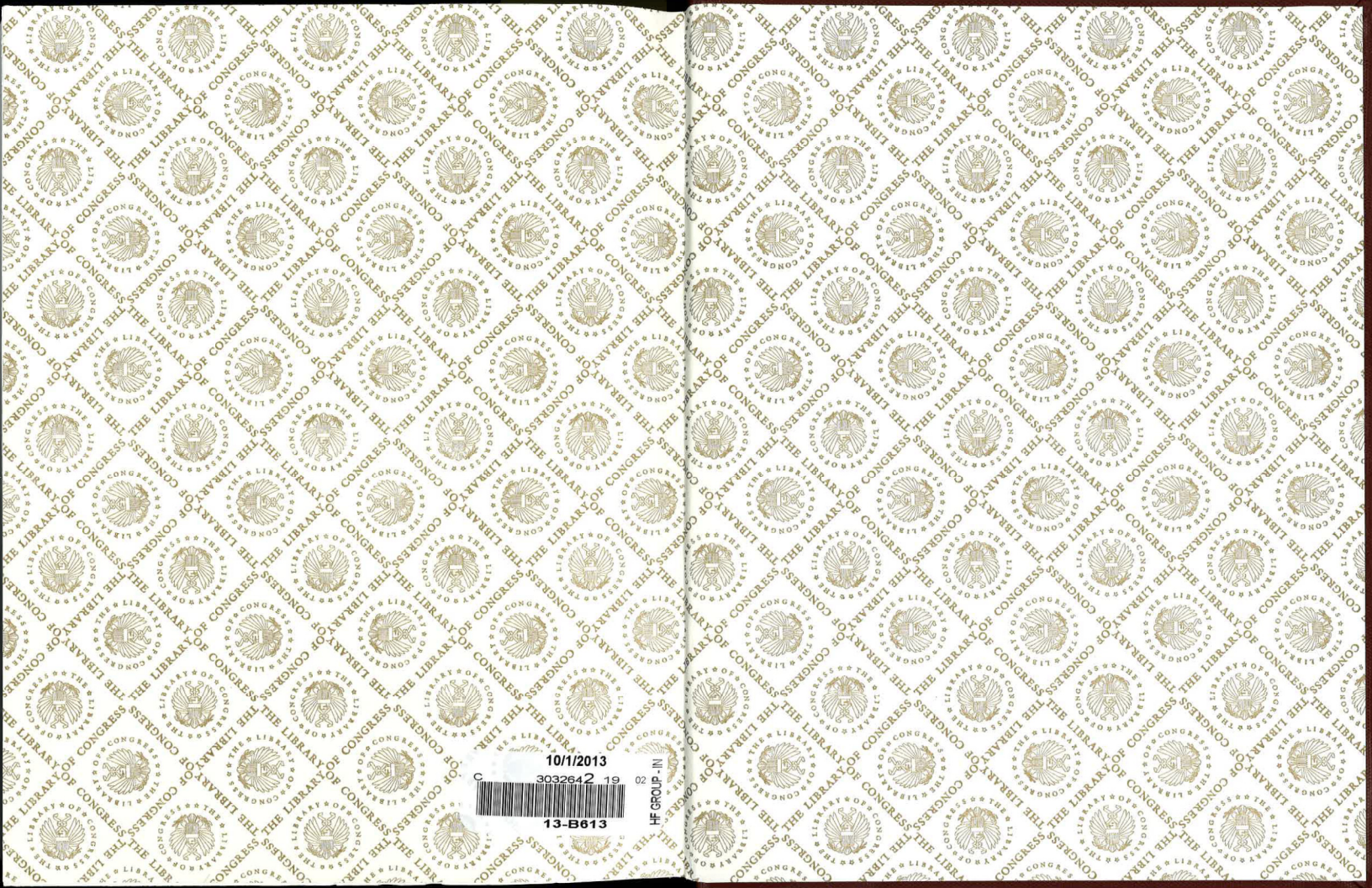
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