Status of Non-Contact Electrical Measurements

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Outline

- Introduction
- Why does the industry want non-contact electrical measurements?
- Review of current status of non-contact electrical measurements
  - Characterization of bulk substrate material
    - Lifetime, diffusion length, iron concentration
  - Characterization of near-surface region
    - Generation lifetime, near-surface doping concentration, near-surface recombination lifetime, minority carrier recovery time (*Epi-*τ)
  - Characterization of dielectrics and interfaces
    - Equivalent oxide thickness *(EOT)*, interface trap density (*Dit)*, soft-breakdown, mobile charge, surface voltage, stress induced leakage current (SILC)
- Summary
- Conclusion

DISCLAIMER

Certain commercial instruments are identified in this review in order to adequately specify the metrology procedures. Such identification does not imply any recommendation or endorsement by Applied Materials, nor does it imply that the instruments identified are necessarily the best available for the purpose

Introduction

- Non-contact electrical measurements:
  - Kelvin, 1881
    - surface potential measurements using vibrating probe
  - Bardeen and Brattain, 1953
    - surface photovoltage (SPV) for semiconductors
  - Goodman, 1961
    - industrial implementation of SPV (RCA)

- Key components of non-contact electrical instruments:
  - Surface potential (surface voltage) measurements
    - in dark
    - under illumination
  - Surface photovoltage (SPV)
  - Corona charge deposition on the surface $\Rightarrow$ "non-contact" bias

Why does the industry want non-contact electrical measurements?

- Non-contact electrical metrology
  - Expands capabilities of traditional electrical testing
  - Provides
    - Full wafer diagnostics early in process steps (before device fabrication)
    - Excellent process step isolation (troubleshooting)
    - Fast measurement turn around
  - Reduces cost of ownership

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Characterization of bulk substrate material

- **Lifetime**
  - Used to measure the defectiveness of semiconductor material
  - Represents recombination processes in the bulk and at the surface
    - Effective minority carrier lifetime (for high lifetime values):

That's what we obtain from the measurements

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{bulk}} + \frac{S_f + S_b}{T}$$

Surface recombination effect on bulk lifetime measurements!!!

That's what we need to measure

where τ_{bulk} → recombination in the bulk region of silicon substrate

S_f → front-surface recombination velocity

S_b → back-surface recombination velocity

T → silicon substrate thickness

Often is unknown

  - Typical applications:
    - Characterization of quality of the incoming wafers
    - Estimation of concentration of heavy metals
  - Non-contact measurement approaches:
    - Several vendors: lifetime from photoconductivity decay (μPCD) analysis of reflected microwave; based on several ASTM standards
    - KLA-Tencor Quantox: lifetime from analysis of SPV transient
    - Several vendors: lifetime calculated from measured diffusion length

Characterization of bulk substrate material

- Diffusion length
  - Used to measure the defectiveness of semiconductor material
  - Related to the bulk lifetime τ_{bulk}, (*D* is a diffusion coefficient):

$$L = \sqrt{D \cdot \tau_{bulk}}.$$

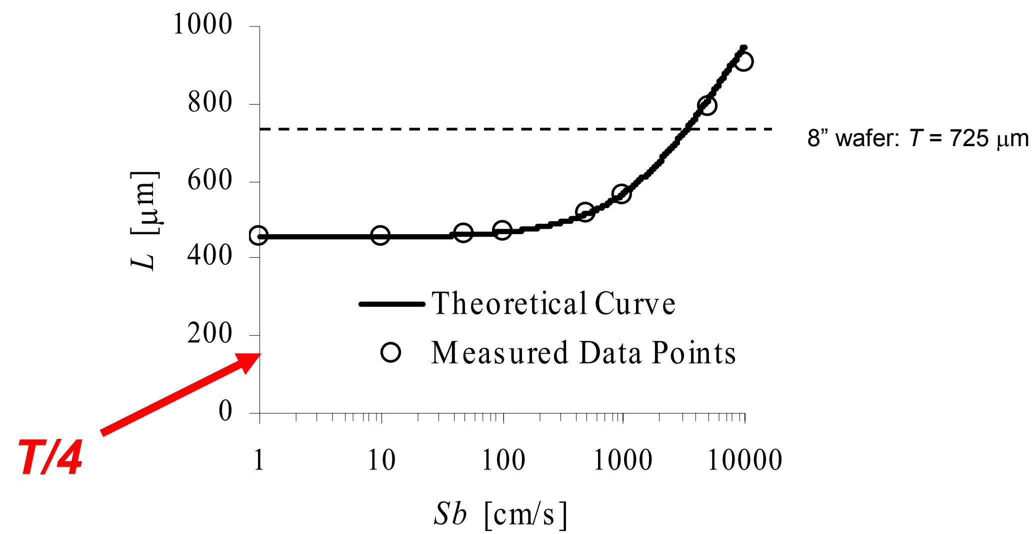
  - Typical applications:
    - Characterization of quality of the incoming wafers
    - Estimation of concentration of heavy metals
  - Non-contact measurements:
    - SPV- based diffusion length measurements
      - ASTM standard F 391-96[1]
        - **ASTM standard F 391-96: no effect of the front surface recombination (by design)**

[1]ASTM F 391 – 96, *Am. Soc. Test. Mat.*, 1996

Characterization of bulk substrate material

- Effect of the back-surface recombination on diffusion length, *L*, measurements
  - Theoretical modeling based on Ref. [1] applied to a range of assumed *Sb* values using 725 μm wafer thickness (standard 8" wafer)
  - Experimental SPV *SDI FAaST-330* measurement for given wafer
    - *L* without any *Sb* correction: SDI "Standard" SPV mode
    - Input *Sb* value in SDI software and measure the given wafer → *L* with *Sb* correction for that *Sb* value: SDI "Enhanced" SPV mode

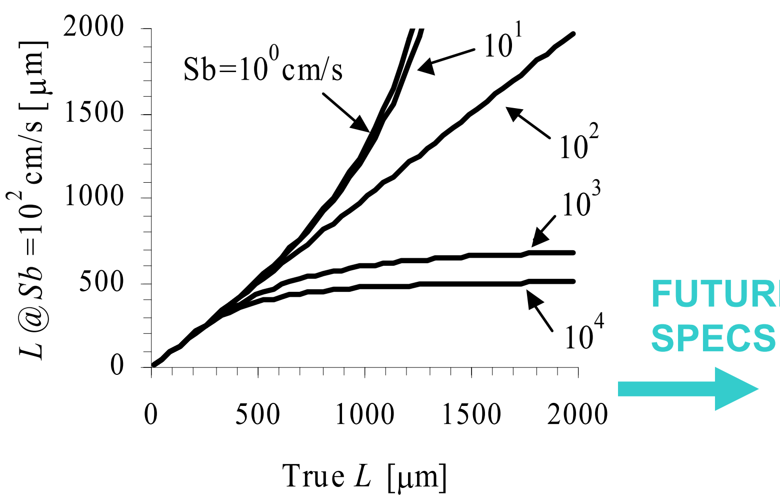
ASTM F 391 – 96 standard[2]:
L ≤ *T/4* → "…for the most accurate diffusion length measurements". This mean that if *L* > *T/4* , **back surface recombination *Sb* must be taken into account**

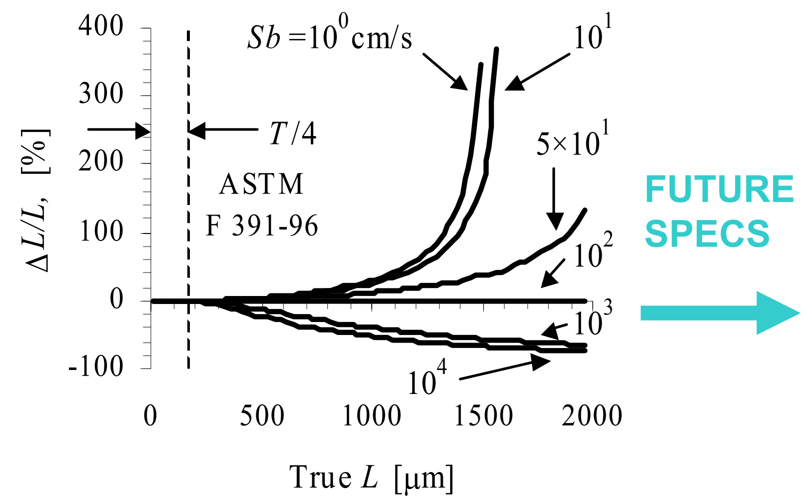


[1]Schroder, D. K., *Semiconductor Material and Device Characterization*, New York: John Wiley & Sons, 1990
[2]ASTM F 391 – 96, *Am. Soc. Test. Mat.*, 1996

Characterization of bulk substrate material

- *Results*: effect of the back-surface recombination on diffusion length, *L*, measurements
  - Oxidized wafer: typical $Sb=10^2$ cm/s (recommended by vendor)
  - Reported[1] *Sb* range: 10^{-1} - 10^4 cm/s





8" wafer: *T* = 725 µm

Back-surface recombination affects the accuracy of diffusion length measurements and becomes more significant at higher values of diffusion lengths

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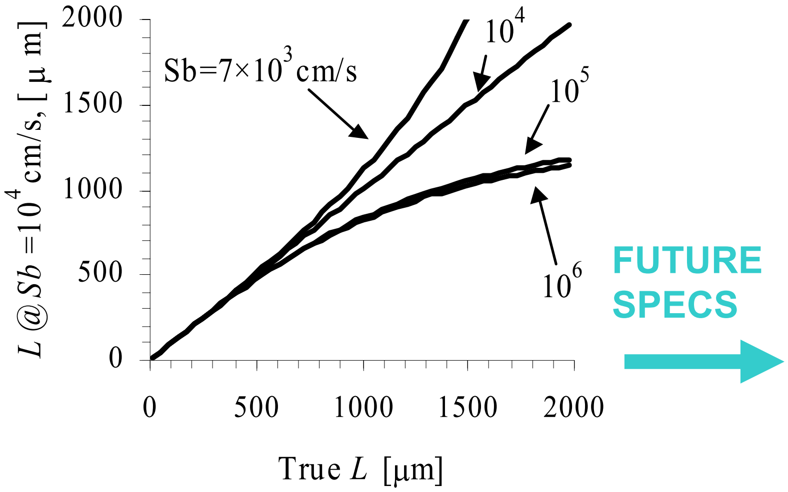
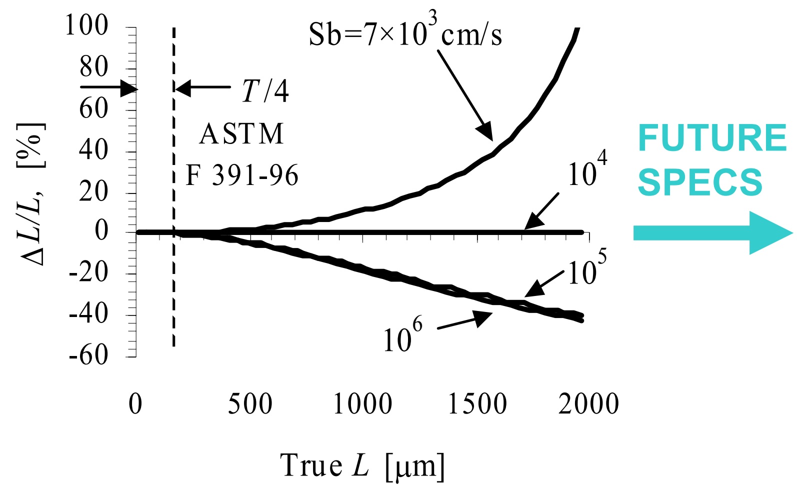
[1]Polignano M.L., Caricato, A. P., A. Modelli, and R. Zonca, *Electrochemical Soc. Proc.* **99**-16, 38-47 (1999)

Characterization of bulk substrate material

- *Results*: effect of the back-surface recombination on diffusion length, *L*, measurements
  - Bare wafer case: typical *Sb*=10^4 cm/s (recommended by vendor)
  - Reported[1] *Sb* range: 7×10^3 - 10^6 cm/s





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Characterization of bulk substrate material

- Surface recombination is a potential problem for ALL metrology suppliers providing the measurement of:
  - Lifetime – effect of both the front- and back-surface recombination
  - Diffusion length – only effect of the back-surface recombination
- SDI (diffusion length based on *ASTM F 391-96*):
  - Allows to input *Sb* value (**if known!!!**) to correct *L* calculations in "Enhanced" mode
  - Does not provide a metrology solution for correction on *Sb*
- KLA-Tencor Quantox
  - Lifetime measurements can be potentially affected by recombination at front and back surface of the wafer
  - Applies front surface conditioning by corona charging to reduce the front-surface recombination effect
  - Does not report any procedures for corrections on the back-surface recombination of the oxidized wafers

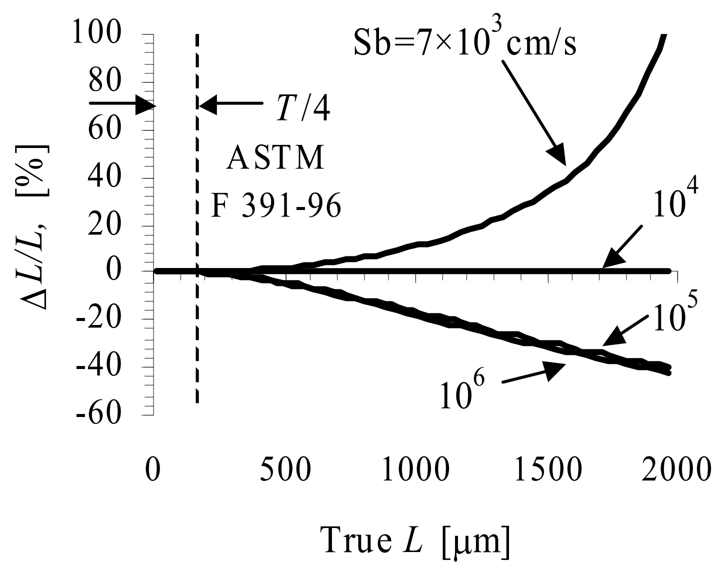
Characterization of bulk substrate material

- SEMILAB
  - Offers a lifetime measurement by μPCD with in-situ wet chemical treatment of the wafer surface – attempt to resolve the front- and back-surface recombination effect problem
  - Assumes that under this treatment conditions the surface is in accumulation and *Sf* and *Sb* are close to zero
  - *However*, still does not measure the actual surface recombination velocity!

- How to measure the surface recombination velocity directly???
  - *Hint / example*: PCR-100 from Photo-Thermal Diagnostics Inc.
    - Provides direct surface recombination velocity measurements
    - *Principles*:
      - Carriers are generated in the near-surface region using laser
      - Carriers recombine on surface states
      - The radiation emitted during recombination is registered using IR detector…

Characterization of bulk substrate material

- Bottom line:
  - ASTM F 391-96 standard for bare wafer diffusion length *L* measurements said *Sb* is not important if *L* < *T*/4, the situation at that time
  - Current *L* up to 3*T* (~ 2000μm)!
    - ⇒ **Huge Error is Possible**



WHAT ACCURACY INDUSTRY WANT / NEED?

Characterization of bulk substrate material

- Lifetime and diffusion length are fundamental parameters for characterization of bulk substrate material quality (if measured accurately!!!)

- The important bottom line question here, for which the metrology community needs an answer from the semiconductor industry, is what uncertainty in true *L* is acceptable. Are 100% variations in determined numbers, associated purely with the sensitivity of the metrology to *Sb*, acceptable?

- Solution of the surface recombination effect problem on characterization of bulk material is
  - Direct measurement of *Sb* during lifetime / diffusion length / iron concentration measurements

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Characterization of bulk substrate material

- Estimate of metal concentration measurements
  - Estimate of iron concentration in *p*-type *B*-doped silicon
    - *Principle*: diffusion length measurements before and after dissociation of the *FeB* pairs (Zoth and Bergholz[1], 1989):

$$[Fe] = 1.06 \cdot 10^{16} \left(\frac{1}{L_{aft}^2} - \frac{1}{L_{bef}^2} \right)$$

  - Estimate of iron concentration in *p*-type *B*-doped silicon
    - *Principle*: lifetime measurements before and after dissociation of the *FeB* pairs:

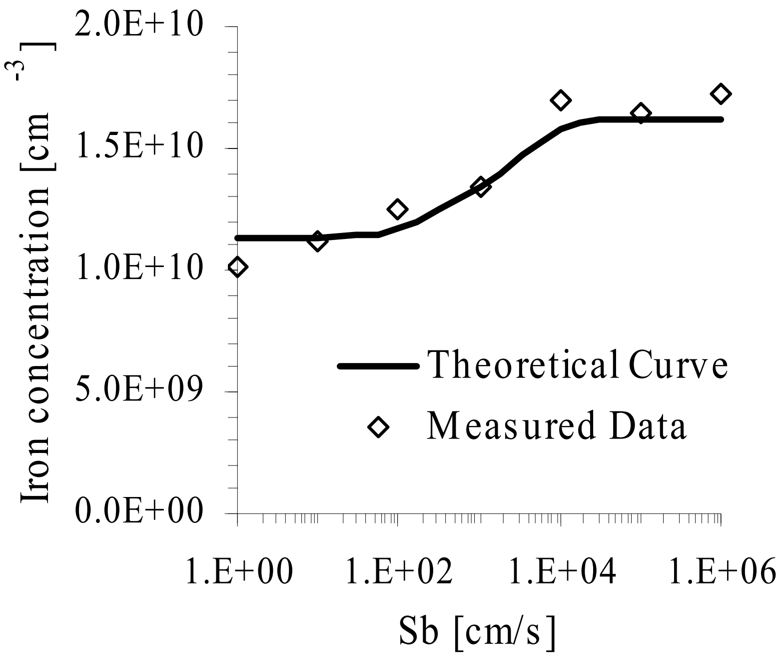
$$[Fe] = Const \cdot \left(\frac{1}{\tau_{after}} - \frac{1}{\tau_{before}} \right)$$

  - Other applications:
    - Copper concentration measurement in bulk silicon (patented by SDI)
      - *Principle*: dissociation of *Cu-Cu* pairs

[1]Zoth, G., and Bergholz, W., *J.Appl.Physics* **67**, 6764–6771 (1990)

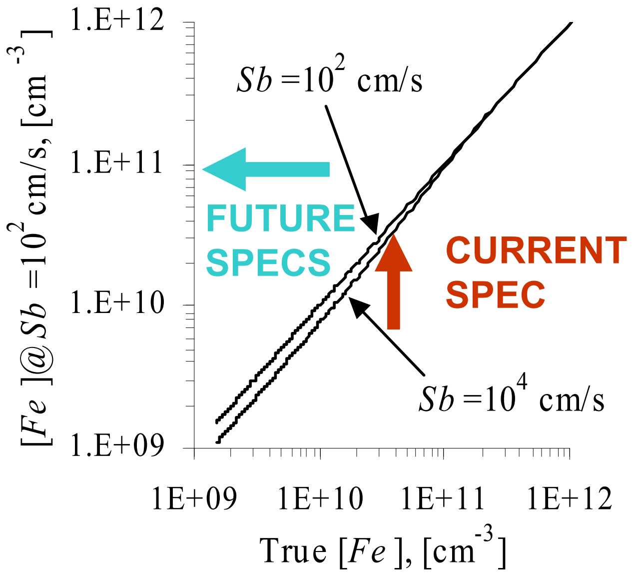
Characterization of bulk substrate material

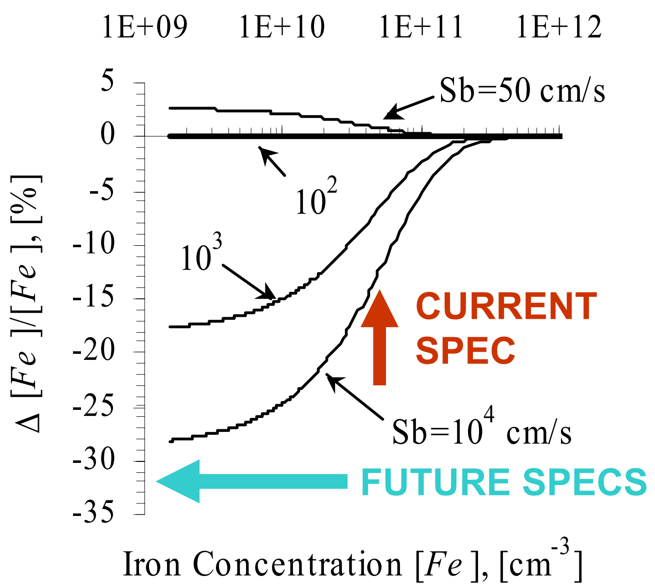
- Effect of the back-surface recombination on the iron concentration [*Fe*] measurements
  - Theoretical modeling performed for different *Sb* correction values
  - [*Fe*] measurements performed using SDI FAaST-330 with "enhanced" mode correction for different *Sb* correction values



Characterization of bulk substrate material

- *Results*: the effect of the back-surface recombination on the iron concentration measurements





Modeling assumption: *Laft* = 80% *Lbef*

Back-surface recombination affects the accuracy of iron concentration measurements and becomes more significant at lower iron concentrations

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Characterization of bulk substrate material

- Surface recombination is a potential problem for ***ALL*** metrology suppliers providing the measurement of iron concentration based on
  - Lifetime – effect of the both front- and back-surface recombination
  - Diffusion length – only effect of the back-surface recombination

AGAIN, REAL GUIDANCE FROM THE INDUSTRY IS NEEDED AS TO WHAT IS ACCEPTABLE

- SDI: Copper concentration measurements
  - SDI SPV-copper method is not sensitive to copper that present in silicon in forms different from the *Cu*-*Cu* complex
  - Is *Cu*-*Cu* complex defect a dominating form of *Cu* presence in bulk silicon?
  - Is there a procedure to convert ***ALL*** copper into *Cu*-*Cu* complexes to be able to use SDI SPV Copper concentration measurements for estimate of copper concentration???

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Characterization of near-surface region

- Generation lifetime

  ...measurements in darkness

  - *Definition*: Generation lifetime is the rate at which minority carriers are thermally generated when there is a ***deficit*** of carriers
  - Used to measure the defectiveness of near-surface material
  - Sensitive to deep levels – lifetime killers with an activation energy in the vicinity of midgap ± $2kT/q$

- Near-surface recombination lifetime

  ...carrier excitation by light

  - *Definition:* Near-surface recombination lifetime is the rate at which ***excess*** minority carriers recombine in the *SCR* near to the surface
  - Used to measure the defectiveness of near-surface material
  - Represents recombination processes in the near-surface region

- Near-surface doping concentration
  - Device parameter

+ recombination???

- Minority carrier recovery time τ_R or *Epi-*τ

  ...carrier excitation by modulated light

  - *SDI Definition*: "This is the time constant of the minority carrier recovery in the surface depletion layer. The τ_R value is controlled by the generation lifetime. It decreases with increasing contamination levels of Ni, Co, Cu, Mo that are not readily detectable in recombination lifetime (τ and L)"
  - Used to measure the defectiveness of near-surface material

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Characterization of near-surface region

- Generation lifetime
  - The KLA-Tencor Quantox generation lifetime, *GLifetime*
    - measured using the **guard ring** to reduce interferences of the surrounding silicon similar to that described in ASTM Standard F 1388 for MOS device measurements of generation lifetime
- Minority carrier recovery time
  - The SDI minority carrier recovery time or *Epi-*τ
    - Alternative to widely accepted generation lifetime
- Near-surface doping concentration
  - KLA-Tencor: **absolute** measurements $\Rightarrow$ **no calibration!** + guard ring
  - SEMITEST: C-V type of **doping profile** in non-contact manner
  - Other vendors (SDI, QC Solutions, others): **no guard ring!…**
    - *Advantage*: **fast measurements**
    - *Disadvantage*: require calibration for every new material;
    - SDI Surface Doping map
      - *Advantage*: **fast whole wafer map!**
      - *Disadvantage*: **non-uniform surface barrier** $\Rightarrow$ map is **inaccurate!**
- Near-surface recombination lifetime (KLA-Tencor Quantox)
  - Suitable for characterization of thin epi-layer material

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Characterization of near-surface region

- Summary:
  - Methods for characterization of near-surface region offered by different metrology vendors are providing expected capabilities
  - There is always room for improvements but…

…these measurements are not showstoppers!

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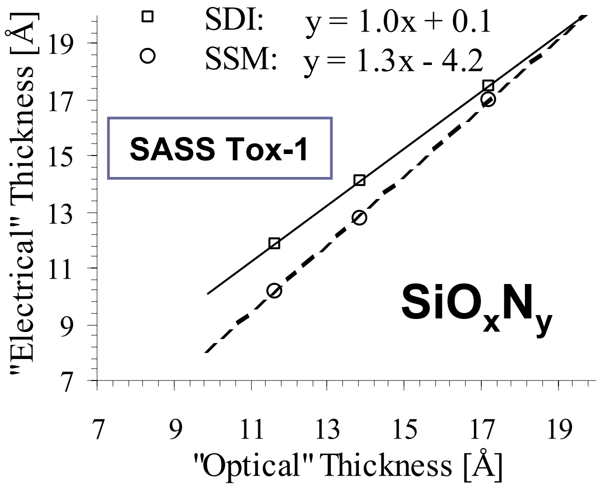
Characterization of dielectrics and interfaces

- Equivalent oxide thickness (*EOT*)
  - *Definition: EOT* of a dielectric film is the thickness that perfect SiO_2 would have for that dielectric film's capacitance value
  - Device parameter; important for characterization of gate dielectric integrity, quality and, in particular, to obtain dielectric constant of material
- Interface traps density (*Dit*)
  - Characteristic of quality of interface between dielectric & semiconductor
- Soft-breakdown
  - Characteristic of dielectrics quality: dielectric strength
- Mobile charge
  - Concentration of charged impurities that diffuse or drift in dielectrics
- Surface voltage
  - Basic component for other non-contact electrical parameters

Characterization of dielectrics and interfaces

- *EOT*: approaches under substantial leakage situation
  - KLA-Tencor Quantox: ***ACTIV***
    - Correction of *Q-V* curve for leakage: ***No experimental data…***
  - SDI: SASS Tox[1]
    - SASS Tox-1
      - <u>*Measures*</u>: the surface voltage at SASS conditions: $J_{corona\ gun} = J_{leakage}$
      - Repeatable and reproducible
      - SDI demonstrated that the SASS Tox-1 correlates to optical thickness, device thickness, *etc*.



      - Additional modeling shows that SASS Tox-1 is insensitive to change of dielectric constant.
    - SASS Tox-2
      - <u>*Parameter*</u>: *EOT* derived from the capacitance measurements
      - <u>*Measures*</u>: capacitance from derivative of the surface voltage decay at *t* = 0 after cease of corona
        - ***No experimental data yet***

US Patent Application Publication US2002/0125900 A1, Savtchouk, A., Lagowski, J., D'Amico, J., Wilson, M. D., and Jastrzebski, L. L., 2002

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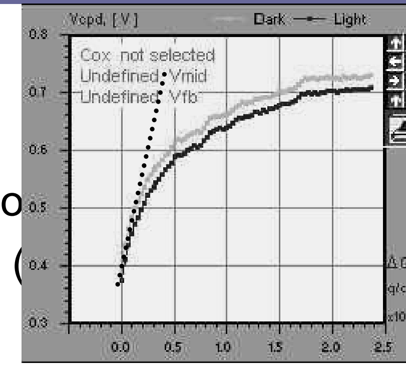
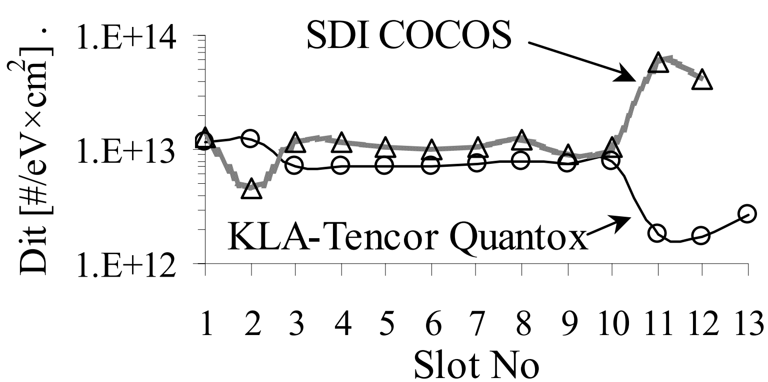
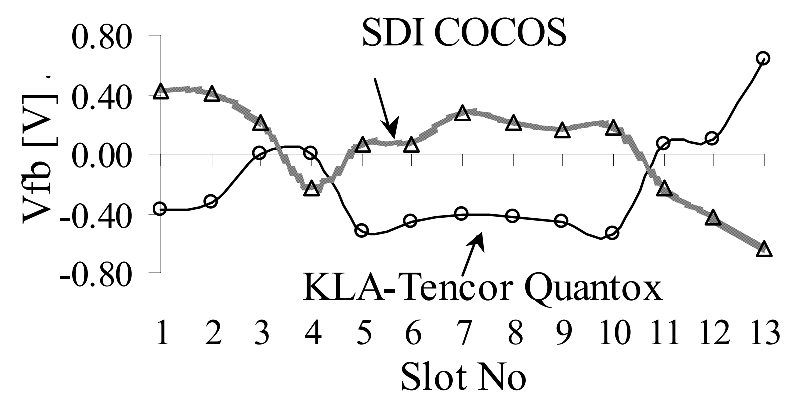
Characterization of dielectrics and interfaces

- Interface state density (*Dit*) measurements
  - *Q-V* measurement approaches:
    - <u>COS</u>: **C**orona-**O**xide-**S**emiconductor (for example, KLA-Tenco
    - <u>COCOS</u>: **C**orona-**O**xide **C**haracterization **O**f **S**emiconductors (
  - Leakage of dielectric affects the measurements



  - Discrepancies in the *Dit* definitions from different suppliers:
    - <u>COS</u>: *Dit* value is calculated at midgap using curves *SPV-V-Qc*
    - <u>SDI COCOS</u>: *Dit* is a value of global minimum of the curve *Dit* vs. *Vsb* derived from curve V_{CPD} vs. *Qc*





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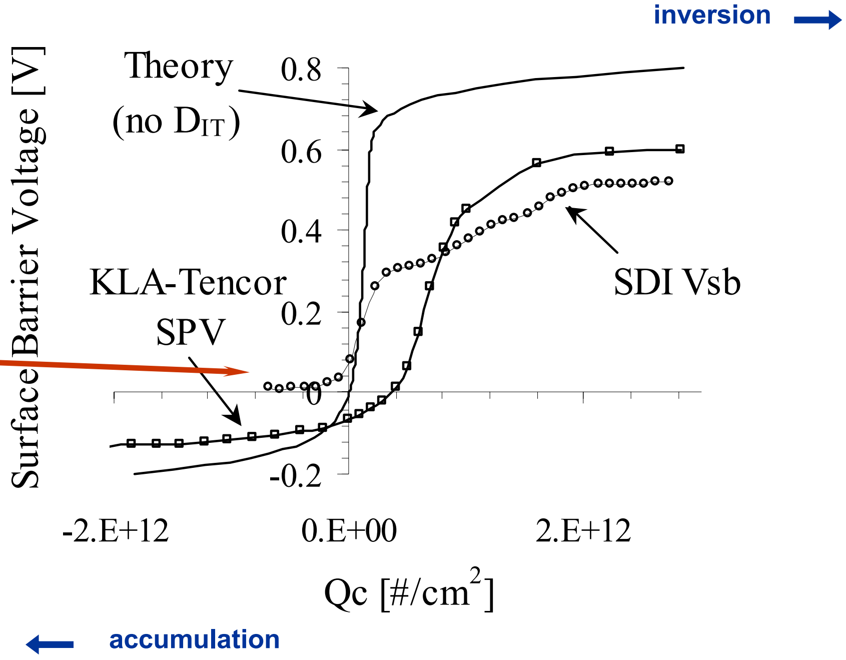
Characterization of dielectrics and interfaces

- Interface state (*Dit*) measurements (cont'd)
  - SDI COCOS issues
    - SDI "surface barrier" *Vsb* nearly reaches the ≈ 2/3 of surface barrier value ⇒ distortion of SDI "*Dit* spectrum", *Dit* vs. *Vsb*
      - **normally, Dit spectrum is dependence *Dit* vs Energy through band gap**
    - *Vsb* vs. *Qc* curve does not change sign: ***Vfb* accuracy problems**?
      - COCOS II and Variable Corona COCOS: original COCOS improvements
        - **no experimental data**

Challenge to obtain the midgap value???

***Vsb* must change sign at flat band conditions… SDI… How was *Vfb* calculated???**



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Characterization of dielectrics and interfaces

- Soft Breakdown measurements
  - Measure of dielectric quality and integrity – dielectric strength
    - *Advantage*: fast whole wafer map
- Mobile Charge measurements
  - Detection of impurity mobile ions
  - Alkali metals (Na, K, Li)
    - Advantage: fast whole wafer map
    - Good for thick oxides: 1000Å
    - Difficult to measure thin dielectrics: *EOT* < 200Å
  - SDI Mobile Copper
    - No reliable repeatability and reproducibility:
      - Cu diffuses through the interface into the silicon (alkali metals tend to stay in oxide)
- Surface voltage measurements
  - SDI surface voltage ≡ "Plasma Damage Monitor" voltage, V_{PDM}
    - Sensitive to dielectric thickness variation
    - Correction for thickness non-uniformity is not provided
  - KLA-Tencor approach to plasma damage using *Vsurf:*
    - KLA-Tencor provides correction of *Vsurf* for thickness variation
    - *Vsurf* + *Vfb* + *Dit* – more comprehensive representation of plasma damage

Summary

- Characterization of bulk substrate material
  - Lifetime and diffusion length are the fundamental parameters for characterization of bulk substrate material quality (**if measured accurately!!!**)
  - Back-surface recombination does affect the accuracy of the lifetime, diffusion length and iron concentration measurements
  - **WHAT ACCURACY IS ACTUALLY REQUIRED?**

- Characterization of near-surface region
  - Methods for characterization of near-surface region provided by different metrology vendors are providing expected capabilities
  - There is always room for improvements but… **these measurements are not show stoppers!**

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Summary (cont'd)

- Characterization of dielectrics and interfaces
  - *EOT* measurements are affected by dielectric leakage
    - KLA-Tencor Quantox: ***ACTIV*** **(no data)**
    - SDI: SASS Tox-1 – excellent reproducibility but does **not** provide *EOT*
    - SDI: SASS Tox-2 – *EOT* **(no data)**
  - *Q-V* measurements (COS and COCOS):
    - Leakage effect is a problem
    - Discrepancies in the *Dit* definitions from different suppliers
    - Need standardization of
      - "*Dit*" parameter definition
      - *Dit* measurement procedure
  - Mobile charge:
    - Challenges for thin dielectric measurements
    - SDI "mobile copper":
      - Cu escapes from oxide ⇒ no repeatability, no reproducibility
  - Surface Voltage measurements:
    - SDI Plasma Damage Monitor voltage V_{PDM} is sensitive to plasma damage, but also to other parameters (e.g. thickness variations)

Conclusions

- Non-contact electrical metrology
  - expands capabilities of traditional electrical testing
  - reduces measurement turn around
  - reduces cost of ownership
- We appreciate the efforts of the suppliers that have taken tremendous business risks in developing this specialized metrology equipment in the fast changing environment of the semiconductor industry needs
- Being the users of these tools, we are also totally relying on commitment of the vendors to deliver expected quality of the metrology instruments to end customers
- The goal of this review is to highlight the critical problem areas in metrology and to encourage customers to provide feedback to suppliers in order to accelerate improvement of the metrology tools
- Additional efforts are still needed to make this promising metrology reliable and standardized in order to address metrology needs of semiconductor industry