2023 6th International Workshop (WECC), Pfeiffer Vacuum

IRDS™ Road Map: Contamination Control and Yield Analysis

Annecy, September 19th, 2023

Jost Kames, IRDS YE Chapter, Co-chair AMC subgroup

INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS™

2023 6th International Workshop (WECC), Pfeiffer Vacuum

IRDS™ Road Map: Targets, Structure & Recent Work in the YE (Yield Enhancement) chapter

(IRDS editions 2022/2023)

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Some terms on IRDS™

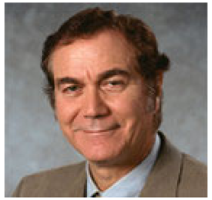
- Institute of Electric and Electronic Engineers (ieee.org)

- TFRC Task force rebooting computing (rebootingcomputing.ieee.org)

- International Roadmap for Devices and Systems (irds.ieee.org)

  - IRDS YE (Yield Enhancement Chapter – dealing with „random effects on yield“ and„contamination“) WECC (wafer environmental control)
    - YE subgroup „AMC – Airborne molecular contamination“
    - YE - all subgroups: Chemicals, Gases, UPW, AMC, Critical Components

IRDS™ - YE Yield Enhancement Chapter



- Paolo Gargini, IRDS chairman / Linda Wilson secretary/editor

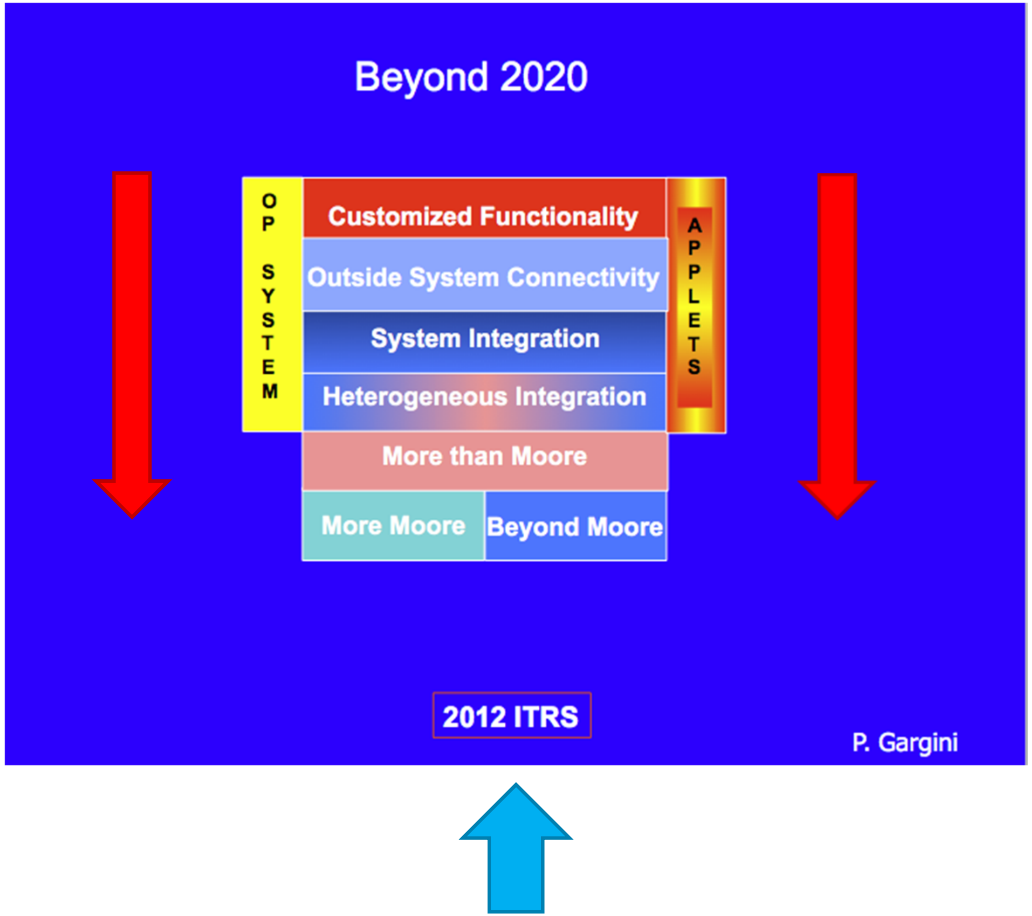
- IRDS YE Chapter, Slava Libman, FTD solutions LLC (chair)

- IRDS YE subgroup AMC, Christoph Hocke, Infineon Technologies (chair), Jost Kames, artemis control AG (co-chair)
  - IRDS YE AMC subgroup: 14 members (IDM, academia, mission critical suppliers)
    - dealing with random (non-systematic) effects & contamination from the clean room environment & tool environment (as long as not in the process step itself)
    - Historically: caring for airborne contamination threats on critical processes on a mandated basis (e.g. lithography, new materials)

IRDS™ History – from NTRS to IRDS

- NTRS (National Technology Roadmap Semiconductor) (1992 – 1997)
  - Set-up after the end of the cold war did no longer fund semiconductor research by DOD
- ITRS (International Technology Roadmap Semiconductor) (1998-2012)
  - Roadmapping for 15 years +; called for international cooperation on red-brick walls, *chip*
  - Industry cooperated in a pre-competitve way (results: strained silicon, HKMG, others)
  - 12 working chapters, finally 17 groups, bottom-up approach, chip tech focussed
- ITRS 2.0 (International Technology Roadmap Semiconductor) (2012-2015)
  - Heterogenous Integration, More-than-Moore (MtM), Roadmapping for 15 years +, top-down approach, system focussed
- IRDS (International Roadmap for Devices & Systems @ IEEE/TFRC)(2016-)
  - Roadmapping for 15 years +; 5 „big picture groups“ (MM), 4 expert groups (e.g. YE)

IRDS™ Mission – identified already in 2012



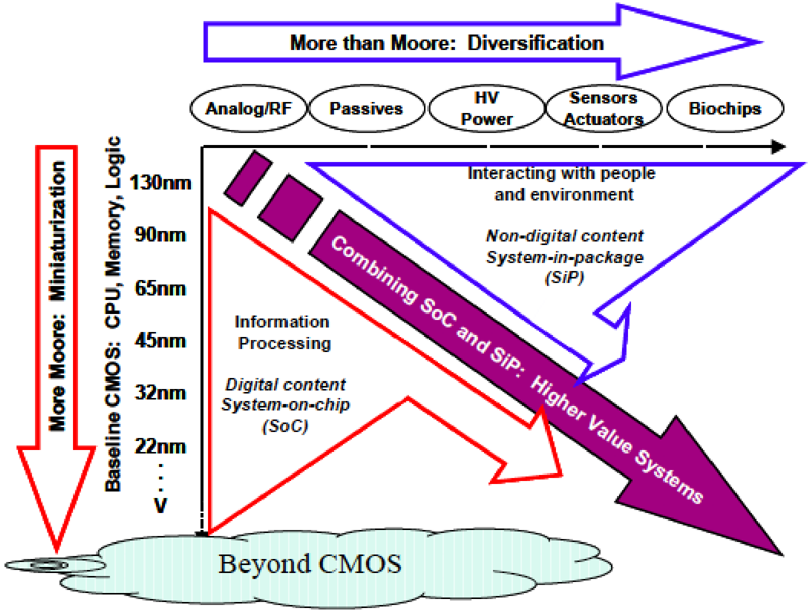


Figure 5 Moore's Law and More

IRDS™ History & Mission – Mission defines structure & content

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- Want to know more about the pathway from NTRs to IRDS?
- Watch out for Paolo Gargini, Chairman, former Intel Director Technical Strategy, e.g. on ieee tv

IRDS Highlights & Future Directions - Paolo Gargini - ICRC San Mateo, 2019

90 views · Download · Share

Published on February 13, 2020

IEEE Future Directions #IEEE #ICRC #Quantum Sessions #Rebooting Computing #quantum computing #MOS #Moores law #Gordon Moore #3D power scaling #new architectures #3D physical limits #Multibit scaling #QIP #quantum information processing #transistors #system architecture #devices #systems #Roadmap

IRDS Chairman, Paolo Gargini, looks at how far computing has come and where it is headed by acknowledging past IRDS events along with a brief recap of the 2019 event. From technology node scaling and creating the ideal MOS transistor to amping up quantum computing as a community, Gargini emphasizes planning within the IRDS Roadmap.

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e.g. 2017:

https://ieeetv.ieee.org/irds-a-new-way-to-roadmap-the-electronics-industry-ieee-rebooting-computing-industry-summit-2017

Advancing Technology for Humanity

IRDS™ History & Mission – Mission defines structure & content

INTERNATIONAL ROADMAP FOR DEVICES AND SYSTEMS™

- "To identify the roadmap of the electronic industry from devices to systems and from systems to devices"

- This is done continuously by IFTs (International Focus Teams)
  - Each of the IFTs will assess present status and future evolution of the ecosystem in their specific field of expertise and produce a 15 year roadmap
  - This includes: evolution, key challenges, major roadblocks and possible solutions
  - Integration of all the IFTs roadmaps will produce a 15-year roadmap
  - Identify the technology needs and the key enablers, potential solutions, and areas of innovations in order to resolve challenges and meet the 15-year targets for the industries enabled by the IRDS™.
  - Identify any potential cooperation with organizations interested to demonstrating possible solutions
  - Identify requirements & estimate solutions implementation time-lines

IRDS™ History & Mission – Mission defines structure & content

- To identify the roadmap of the electronic industry from devices to systems and from systems to devices (identify drivers & road-blocks)
- IRDS has mainly an „inside-to-outside“ approach – make „blocks“ public

- Therefore - how does IRDS work and gets to roadmap results ?
  - IRDS works on a pre-competitive basis, beyond IP considerations
  - IRDS works with experts from IDMs, institutes, suppliers that leave their company hat at the entrance of the (virtual) meeting room and are entitled to contribute for the entity they are from on the above basis
  - IRDS contributors are acting on an FOC basis, regularly, on a peer-to-peer basis. IRDS work is „literature based“ – must be supported by literature
  - IRDS knows "acknowledgement" but no honours as "senior", "fellow"
  - IRDS is working to identify <u>"potential technological gaps</u>" – early enough to enable "the community"/"the market" to work on potential solutions

Manufacturable solutions exist, and are being optimized	
Manufacturable solutions are known	
Interim solutions are known	◆
Manufacturable solutions are NOT known	

IRDS™ History & Mission – Mission defines structure & content

- To identify the roadmap of the electronic industry from devices to systems and from systems to devices (identify drivers & road-blocks)
- IRDS has mainly an „inside-to-outside“ approach – make blocks public

- What IRDS is not doing:
  - IRDS does not work on any type of standardization (task of SEMI)
  - IRDS does not work on any manufacturing guidelines or best-practices
  - IRDS is not working on or promoting solutions („if a solution exists there is no road block“; comment in the report narrative „solutions exist“)
  - IRDS is however screening technologies whether a solution exists or a potential solution exists
  - IRDS is not supposed to create any commercial case by promoting solutions/commercial leads merely on assumptions about “a problem could exist” or “line shrinking leads to increased defects & reduced limits”

Manufacturable solutions exist, and are being optimized	
Manufacturable solutions are known	
Interim solutions are known	
Manufacturable solutions are NOT known	

IRDS™ Mission – Structure & Ways of Communication

- Deliverables: IRDS reports by IFTs (International Focus Teams)
  - IRDS Road-map reports (full-editions / updates) (annually – may stretch to biannually)
  - IRDs Chapter Reports (as YE Yield Enhancement Chapter Report)
  - Within the YE Chapter report, the structure is
    - The "narrative" part of the chapter ("Drivers, Focus Areas, Challenges, past challenges – now solutions")
    - Tabulations within the "narrative chapter" (e.g. "Potential solutions")
    - The "tabulation" part of the chapter ("YE1 – YE5"), most prominent "YE3 – Technology Requirements for Surface Environmental Contamination Control") – often seen as "Table of Contamination Concentration Limits" merging the sub-group requirements AMC, Gases, Chemicals and UPW Ultrapure Water)
  - IRDS public conferences and workshops
  - IRDS contributions e.g. to UPM or workshops as today

Manufacturable solutions exist, and are being optimized	
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Interim solutions are known	◆
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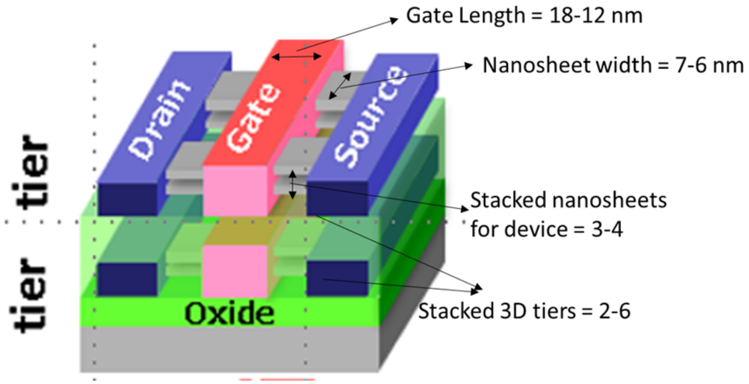
IRDS™ (YE) Yield Enhancement Chapter 2022 - 2024

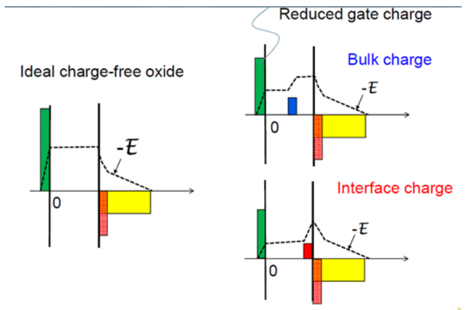
- YE chapter revised (removed solutions, speculations, disconnects)
- YE has a strong „top-down" connection to MM „More Moore"

- Drivers identified are
  - HPC (High performance Computing) / cloud
  - Logic-memory interconect
  - Transfer of typical server/AI/consumer technology into applications with failure proof operations (automotive, transport); prevent failures with fatile effects

  - Hence for the last two years the aspects of "chip production yield" stood back behind "Chip reliability – prevent device failure for > 10 years"
  - Technological focus has been and is still GAA (Gate-all-around) technology
  - MM provides qualitative & quantitative limits for defects & contaminations
  - YE is engaged in contamination pathways and contamination limits

IRDS Yield Enhancement Chapter 2022 – 2024 – MM & YE





Contaminants	Type	Module	Process Step	Mechanism	Cleaning Agent	Mitigation	Defect of Process	Defect Density as measured	Comments
Carbon	atomic post thermal treatment	Source Drain and Gate Stack	Dry Etch	Surface damage blocking the dopant (B, P) diffusion in the extension region	H2 Bake and DIR	Reduce outgassing		5e13 at/cm2	last step, air break after the cleaning
Organics	molecular	Gate stack	Std Clean	Carbon compounds induces the expansion of the silicon oxide lattice, deteriorating the silicon oxide layer, resulting in the device failure	Rinse and Dry	Cleanroom infrastructure		5e11 at/cm2	Sources of organic contamination are chemical surface modification (i.e. hexamethyldisilazane priming), wafer box storage and extended vacuum exposure. Major organic molecules in the cleanroom air are volatiles outgassing from polymeric materials. Affecting subsequent CVD steps controlling the film thickness.
Oxidizers	H2O2, O2, O3	S/D, MOL, metal	Air break, thermal anneal	Si and/or metal oxidation	DHF or SC1	Reduce air break		1e10 at/cm2	oxygen and moisture in the ambient air. Si-O-Si, Si-H and Si-OH species. very dilute solutions of HF, in de-ionized water, DI, or dilute solutions of ammonium fluoride, NH4F, HF and DI water (buffered oxide etch, BOE) completely remove silicon native oxide, leaving a hydrogen-terminated clean silicon surface a.

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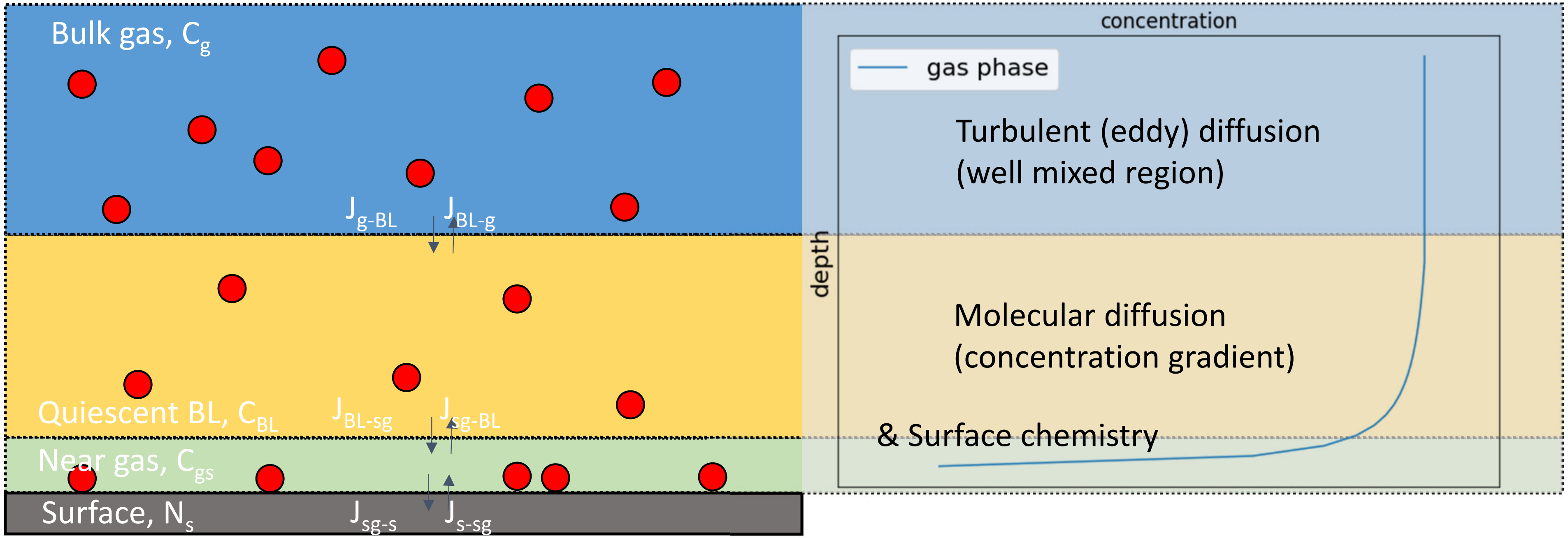
YE Challenges – AMC – convert defect limits to limit concentrations

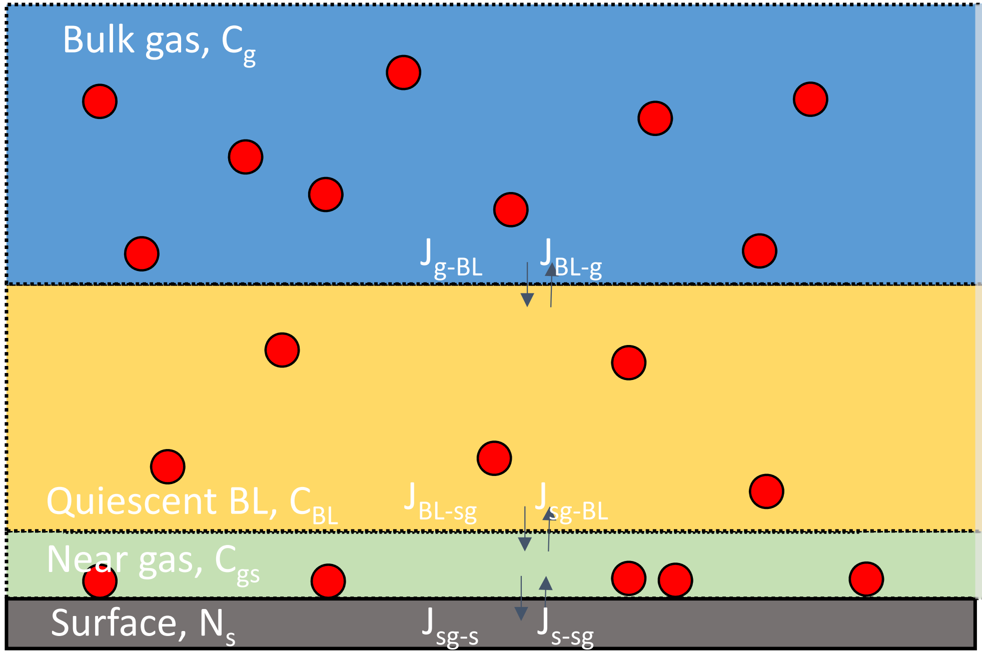
- Gate stack criticality – suspected limits for defect formation expressed as coverage:
  - Carbon (atomic) (post thermal treatment / blocking dopant step) — 5×10^{13} at/cm^2
  - Organic molecules (as SMC from AMC/SVOC deposition / SiO lattice expansion) — 5×10^{11} at/cm^2
  - [Ionic & non-ionic metals (V_t shift and k-value shift to gate-dielectric)] — 2×10^{10} at/cm^2
- Source/drain module / MOL / metallization
  - Oxidization (H_2O_2, O_3, O_2 / unwanted Si and metal oxidation) — 1×10^{10} at/cm^2
- MM YE identified pathways – in relation to AMC as source term – are air break periods and FOUP outgassing or cross-contamination
- Defect creating limits stretch by a factor 5‘000 (1×10^{10} – 5×10^{13} at/cm^2); a detailed examination of AMC deposition & dose modelling is necessary to identify intrinsicly safe situations or AMC limits

YE AMC Boundary layer model – transfer of bulk AMC to SMC



- Model structure: a three-compartment model for the gas-phase and a 4^{th} compartment (surface)
- A concentration gradient in the normal direction to the surface (one-dimensional)
- A transport mechanism through molecular diffusion in the quiescent boundary layer

YE AMC Boundary layer models – A, A* - resistivity models



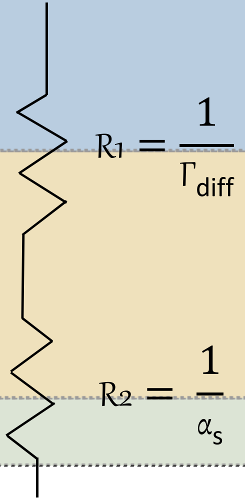
γ – the net uptake coefficient

$$\frac{1}{\gamma} = \frac{1}{\Gamma_{diff}} + \frac{1}{\alpha_s}$$

normalized to the collision rate:

$$\Gamma_{diff} \sim \frac{4 * D_g}{\delta_{BL} * \bar{u}}$$

α_s – the "sticking" coefficient (surface reaction probability between 0 and 1)



δ_{BL} - indoor fluid-mechanical BL range in thickness from 0.5 to >2 cm

D_g - the diffusion coefficients for organic compounds in air at 25°C range from $2E^{-6}$ to $1E^{-5}$ m^2/s

- For δ_{BL}= 0.5 cm Γ_{diff} is ~$n*10^{-5}$

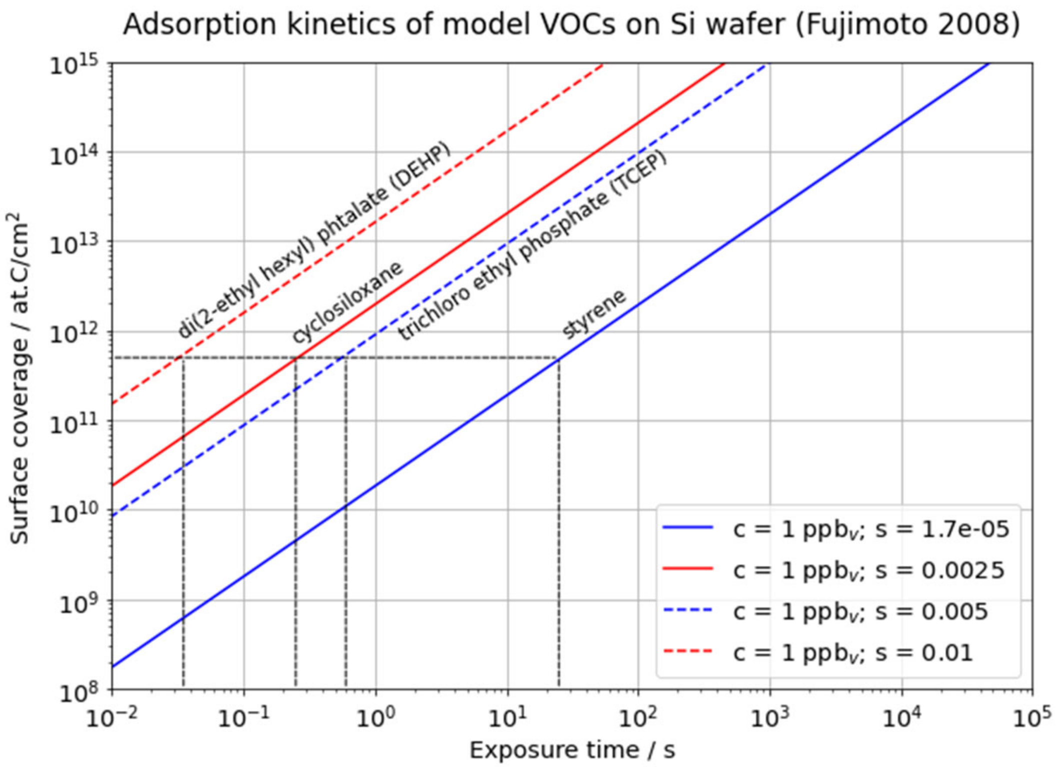
YE AMC- Continuation of model development – model B

- Model A:
  - Simplified boundary layer & resistance model; surface collision controlled version
  - Relies on correctly determined sticking coefficients α_s in a region in which α is rate determining
  - Shortfalls: „incorrectly“ determined α are published / infinite loadings, coverage of surfaces /strictly linear

- Model A*:
  - Full boundary layer & resistance model; mixed diffusion & surface collision controlled version
  - Relies on either correctly determined sticking coefficients α_s and D_g or fully transparent γ_{net} factors
  - Shortfalls: γ_{net} published often refer to non-relevant systems / infinite loadings, coverage of surfaces /strictly linear

- Model B:
  - Model considering surface coverage, surface saturation, release, back-transport, incremental slices for the diffusive layer
  - MATLAB based numerical solution to ODE (ordinary differential equations)
  - <u>Allows to fit experimental data published independently to obtain the system parameter sets</u>

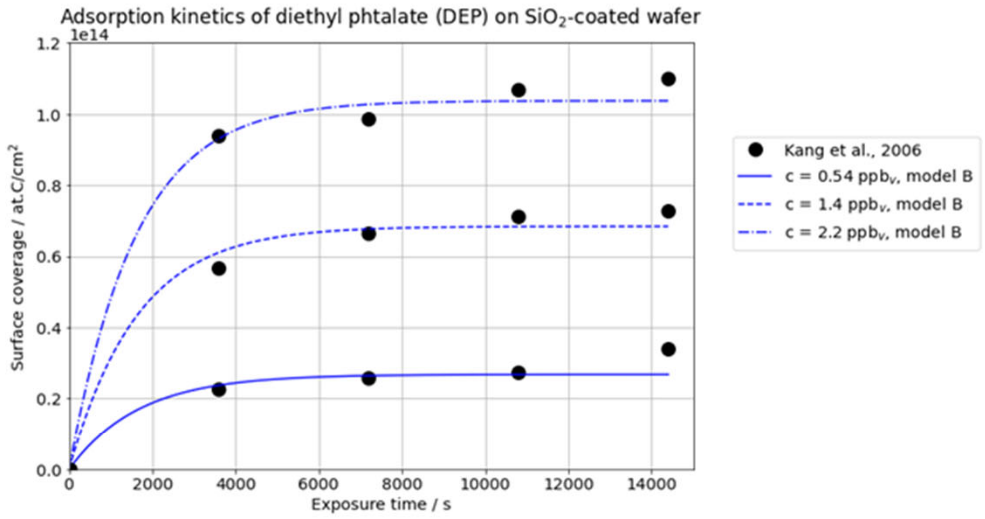
YE AMC - simplified Models A (& A*) – strictly linear uptake

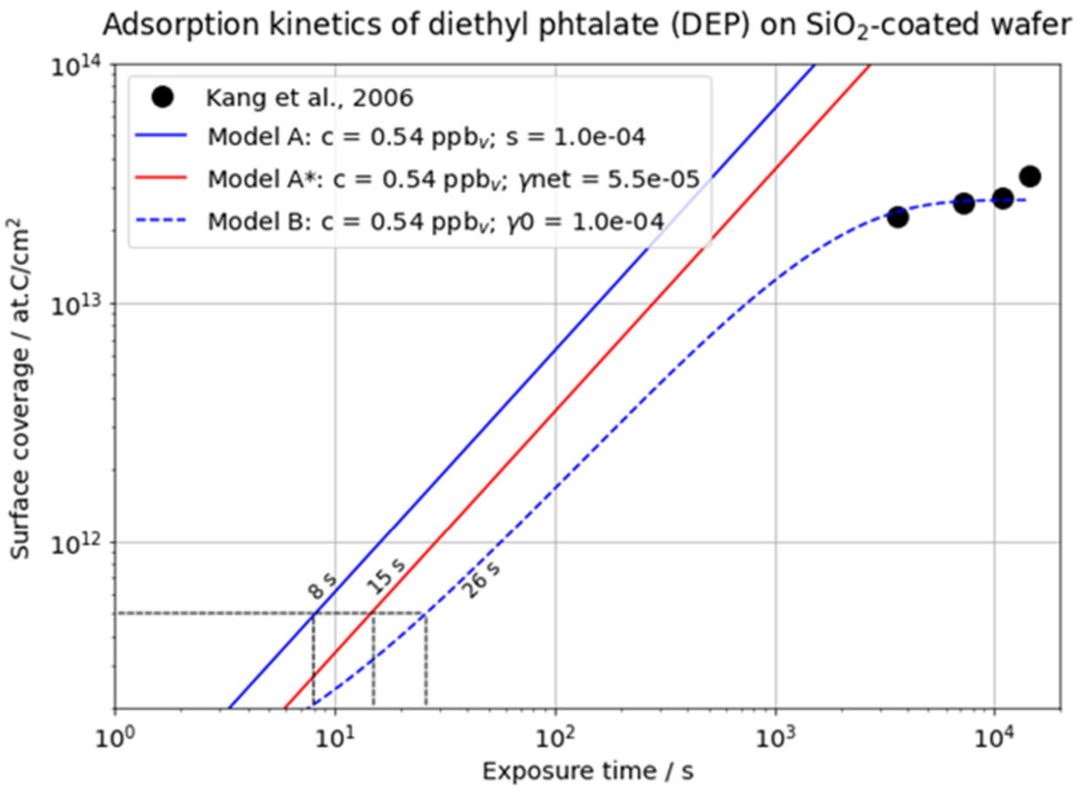


- Model approaches A & A* show a strictly linear increase of SMC over time without effects of surface saturation and back-diffusion/revolatilization
- Both models are of therefore of limited value to describe the AMC – to – SMC transition

YE AMC - Continuation of model development – Model B

- Model B:
  - Left: Fit experimental data published to obtain a model data set; example
  - Right: model the plot of MM/YE AMC (Model B, compared to Model A & Model A* - unlimited uptake)





Linking MM Targets with AMC doses (c_g, t_{crit}) by Model B

Contaminants	Type	Module	Process Step	Mechanism	Defect Density as measured	Model substances	Comments & potential failure mechanism
Carbon	atomic carbon, post thermal treatment	Source Drain and Gate Stack	Dry Etch	Surface damage blocking the dopant (B, P) diffusion in the extension region	$5e^{13}$ at/cm^2	DEP, DBP, DOP, Ethylpropionate	can occur on air break after cleaning, Deterioration of device performance is explained by means of which the positively ionized carbons at the interface acting as additional positive charges affecting the inversion to n-channel
Organics	molecular	Gate stack	Standard clean	Carbon compounds induces the expansion of the silicon oxide lattice, deteriorating the silicon oxide layer, resulting in the device failure	$5e^{11}$ at/cm^2	DEP, DBP, DOP, Ethylpropionate	Sources of organic contamination are chemical surface modification (i.e. hexamethyldisilazane priming), wafer box storage and extended vacuum exposure. Major organic molecules in the cleanroom air are volatiles outgassing from polymeric materials. Affecting subsequent CVD steps controlling the film thickness.
Oxidizers	H_2O_2, O_2, O_3	S/D, MOL, metal	Air break, thermal anneal	Si and/or metal oxidation	$1e^{10}$ at/cm^2	ozone	oxygen and moisture in the ambient air. Si-O-Si, Si-H and Si-OH species. very dilute solutions of HF, in de-ionized water, DI, or dilute solutions of ammonium fluoride, NH_4F, HF and DI water (buffered oxide etch, BOE) completely remove silicon native oxide, leaving a hydrogen-terminated clean silicon surface a.

YE - MM Targets vs. AMC doses (c_g, t_{crit}) by Model B

Model substance	Defect density limit	Impact concentration c_0	Critical time t_{crit}
DEP (Diethylphtalate)	$5e^{11}$ at C/cm^2	1000 ppt_v	22 sec
		100 ppt_v	228 sec
		10 ppt_v	∞
	$5e^{13}$ at C/cm^2	1000 ppt_v	∞
		100 ppt_v	∞
		10 ppt_v	∞
DOP (Dioctylphtalate)	$5e^{11}$ at C/cm^2	1000 ppt_v	14 sec
		100 ppt_v	143 sec
		$\ll$ 1 ppt_v	∞
	$5e^{13}$ at C/cm^2	1000 ppt_v	1’430
		100 ppt_v	15’500
		18 ppt_v	∞

YE - Status & results – Modeling – AMC-to-SMC transition

- Model B:
  - Model considering surface coverage, surface saturation, release, back-transport, incremental slices for the diffusive layer
  - MATLAB based numerical solution to ODE (ordinary differential equations)
  - Allows to fit experimental data published independently to obtain the system parameter sets

- Model substances – applications & extensions:
  - Suitable experimental work published to extract system parameters is sparse
  - System must fit to semiconductor application (Si, SiO); experimental conditions must be transparent
  - For IRDS edition YE 2023 six organic compounds could be evaluated/fitted/parameterised
  - For IRDS edition YE 2024, oxidizers, (at least) ozone to Si as oxidizer will be added

- Results / Gaps / risks identified in the sense of IRDS roadmapping MM/YE:
  - Inherently/Intrinsicly safe AMC concentrations/doses refering to gate stack limits are very low (risk)
  - Inherently/Intrinsicly safe AMC concentrations/doses refering to source drain limits manageable (no risk)
  - Interface to „next step after AMC deposition" (including cleaning, pumping) needs to considered & included

Take-aways from IRDS YE AMC – 2022/2023 – this workshop

- Relating MM defect limits to YE AMC: a model (B) exists for deposition per substance
  - Model considering surface coverage, surface saturation, release, back-transport, incremental slices for the diffusive layer
  - Needs time-resolved experimental SMC data to obtain the system parameter sets

- Results / risks identified in the sense of IRDS roadmapping MM/YE:
  - Inherently safe AMC concenctrations/doses refering to source drain limits „$5e^{13}$ at C/cm^2"(no risk)
  - No inherently safe AMC concenctrations/doses refering to gate stack limits „$5e^{11}$ at C/cm^2" (*risk*)

- Gaps / risks identified in the sense of IRDS roadmapping MM/YE:
  - If we have a clear difference between „$5e^{13}$ at C/cm^2"(no risk) and „$5e^{11}$ at C/cm^2" (*risk*) – how sure are we about risk limits as „$5e^{11}$ at C/cm^2" (*risk*) – considering e.g. FOUP conditions
  - Does the industry know about SVOC monitoring capabilities for 10 – 300 ppt_v per compound (yes, solution for self-control available, no technological gap)
  - Does the industry posses SVOC removal capabilities for 10 – 300 ppt_v from air per compound (yes, solution exist, no technological gap)

Take-aways for IRDS YE AMC – 2024 - challenges

- Updating the IRDS YE chapter

  - Modelling approach has been introduced in the narrative part of IRDS YE 2023 edition (still to be published)
  - YE subgroup AMC will need to find the appropriate way how to adress the „limits" table YE3

Table YE3 Technology Requirements for Surface Environmental Contamination Control

Year of Production	2021	2022	2023	2024	2025	2026	2027
Logic industry "Node Range" Labeling (nm)	"5"	"3"	"3"	"3"	"2.1"	"2.1"	"2.1"
Logic device structure options	FinFet	finFET LGAA	finFET LGAA	finFET LGAA	LGAA	LGAA	LGAA
MPU/SoC Metalx ½ Pitch (nm)[1,2]	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Critical particle size non-electrically active (non-EAP) (nm) based on 50% of Logic 1/2 Pitch (nm (contacted) [1]	10	9	9	9	7	7	7
Critical particle size (nm) of Electrically Active particles based on 50% width of fin Logic SiGe Front End or other device critical dimensions for LGAA **(>2 monolayers)**	3.5	3	3	3	3.5	3.5	3.5
Critical size (EUV mask), nm	12	12	12	12	12	12	12
Gate stack (Gate oxide and gate oxide pre-clean), POE (Point of Entry)							
Total Inorganic Acids (HF, HCl, HBr, HNO3, H3PO4, H2SO4, excluded HNO2); POE	4000 (total) / 500 (individual)	2000 (total) / 500 (individual)	2000 (total) / 500 (individual)	2000 (total) / 500 (individual)	tbd	tbd	tbd
Total Organic and Inorganic Bases	1'000	1'000	1'000	1'000	tbd	tbd	tbd
Total Organics > C6 , (aliphatics, conjugated, ketones, aldehydes, esters and others w/ GCMS retention times ≥ benzene, calibrated to hexadecane) *[31]* POE	1'000	1'000	1'000	1'000	tbd	tbd	tbd
Total Organic Compounds and Inorganic compounds that contain P, B, As (Dopants), POE.	100	100	100	100	tbd	tbd	tbd
~~***Source Drain Contact module (Trench Etch & EPI), POP***~~							
Source Drain Contact module (Trench Etch & EPI), POE (Point of Entry)							
Inorganic Acids (HF, HCl, HBr, HNO3, H3PO4, H2SO4, H2SO3, SO2; excluded HNO2), each; POE	10	10	10	10	tbd	tbd	tbd
Total Organic and Inorganic Bases; POE	100	100	100	100	tbd	tbd	tbd
Total Organic Acids [30]; POE	100	100	100	100	tbd	tbd	tbd
Total Organics > C6 , (aliphatics, conjugated, ketones, aldehydes, esters and others w/ GCMS retention times ≥ benzene, calibrated to hexadecane) *[31] [52]*	100	tbd	tbd	tbd	tbd	tbd	tbd
Total Organics > C6 , (aliphatics, conjugated, ketones, aldehydes, esters and others w/ GCMS retention times ≥ benzene, calibrated to hexadecane) [31]; POE	**100**	100	100	100	tbd	tbd	tbd
Total Organic Acids [30]; POE	**500**	500	500	500	tbd	tbd	tbd
Reactive Sulfur compounds (e.g.: H2S); POE	**500**	500	500	500	tbd	tbd	tbd
Total Organics > C6 , (aliphatics, conjugated, ketones, aldehydes, esters and others w/ GCMS retention times ≥ benzene, calibrated to hexadecane) *[31] [52]* *POE*	1000	tbd	tbd	tbd	tbd	tbd	tbd
Total Organics > C6 , (aliphatics, conjugated, ketones, aldehydes, esters and others w/ GCMS retention times ≥ benzene, calibrated to hexadecane) [31]; POE	1000	1000	1000	1000	tbd	tbd	tbd
Oxidizers (e.g. Ozone); POE	5'000	5'000	5'000	5'000	tbd	tbd	tbd
Ultrapure Water [29]							
Total organic carbon (ppb) [22] for immersion litho, POE	<1	<1	<1	<1	<1	<1	<1
Critical Organics as C (ppb) [22], POE	<1	<1	<1	<1	<1	<1	<1

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Thank you for your attention

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