ATOM PROBE TOMOGRAPHY (APT) :

METROLOGY FOR FUTURE 3D SEMICONDUCTOR DEVICES

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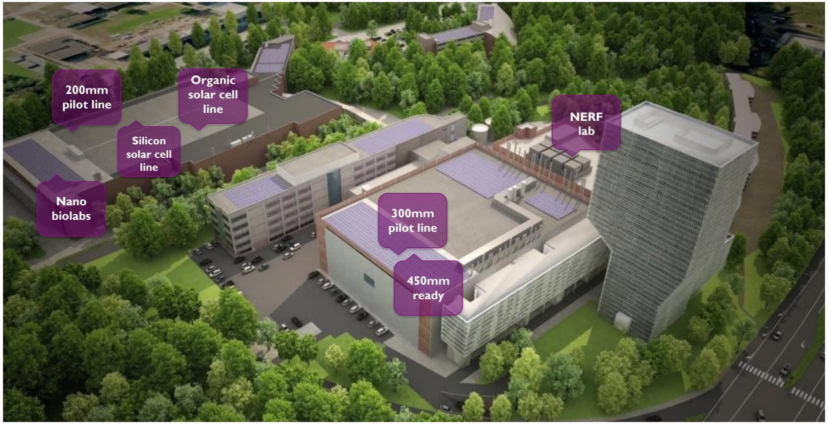
SENIOR FELLOW IMEC

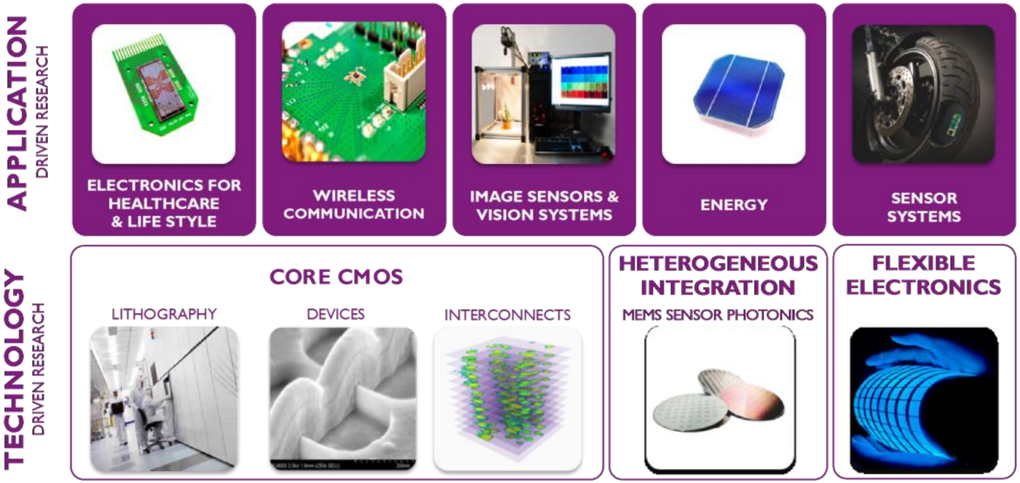
PROF KULEUVEN

ELECTRONIC DEVICES, THE CORE ELEMENTS IN OUR modern SOCIETY

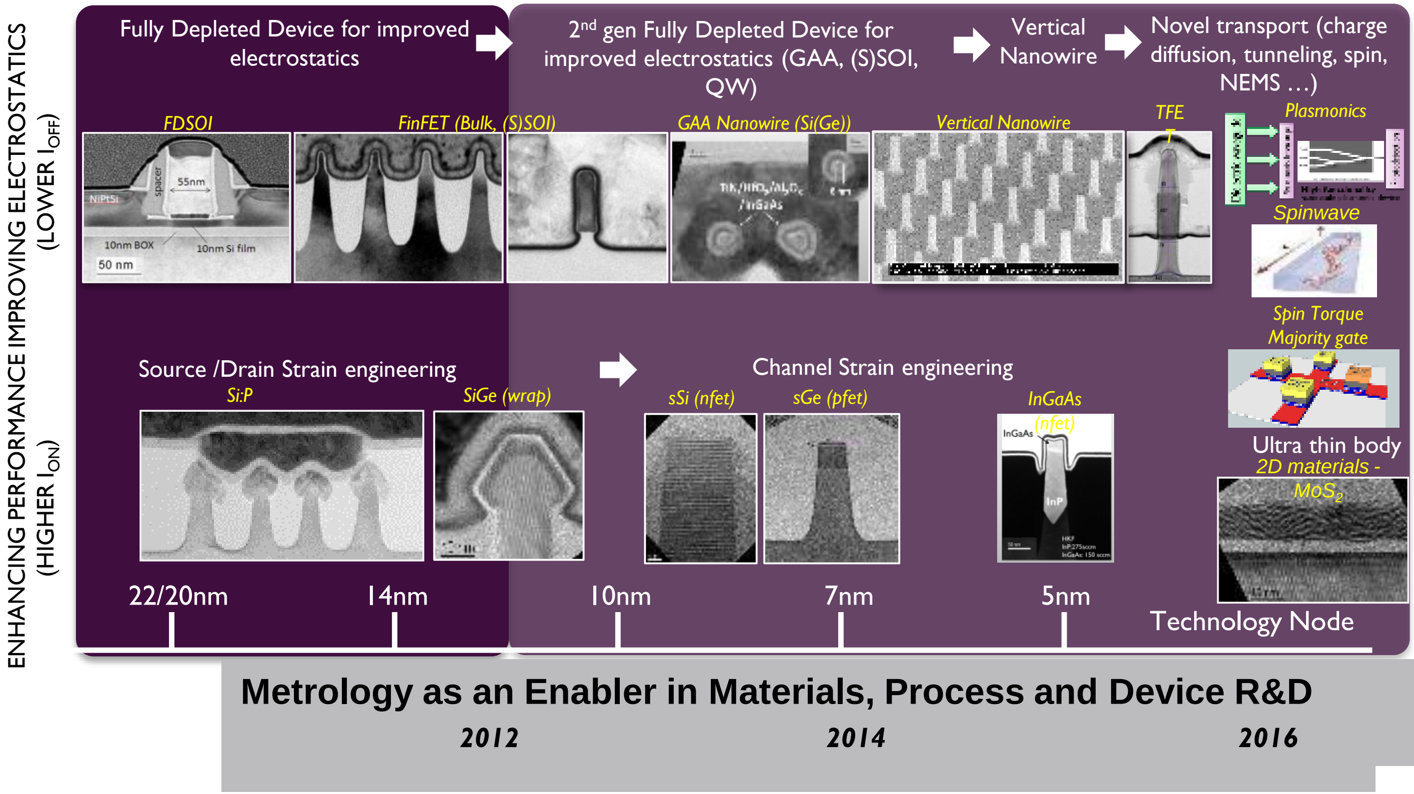
Demand cheap, reliable, high-performance devices

Research programs





Logic Roadmap and its impact on metrology



INNOVATIONS AND COLLABORATIONS : MEETING THE METROLOGY CHALLENGES

R&D

- Metrology for FINFET, TFET, 3D structure
- Metrology for interfacial layers, dopants a concentrations,
- Metrology at near-atomic scale dimensio

LAB : RESOLUTION on INDIVIDUAL DEVICES

Manuf.

- Statistical relevance of single atom detection
- Measurements on test structures must reflect in-die performance
- Time to data/link to process control

FAB : RELEVANT DATA with VOLUME/TAT

Expertise, experience and infrastructure

Materials and processing ← → Metrology

Process and devices

- Multitude of material options & processing techniques
- Combination of new materials & architectures
- nano-scaled (3D)-dimensions

Physical, chemical and electrical characterization

- XPS, AES, (TOF)SIMS, RBS, MEIS, Raman, FTIR, APT ...
- TEM, FIB, SEM, SPM (SSRM, AFM, STM), XRD ...
- Synchrotron based analysis (HAXPES, NEXAFS, EXAFS)

Metrology challenges

Materials

- Si, Ge, III-V, high K, MoX_2,
- metal organic framework,
- organic-inorganic thin films,
- organic semiconductor
- block co-polymer
- graphene

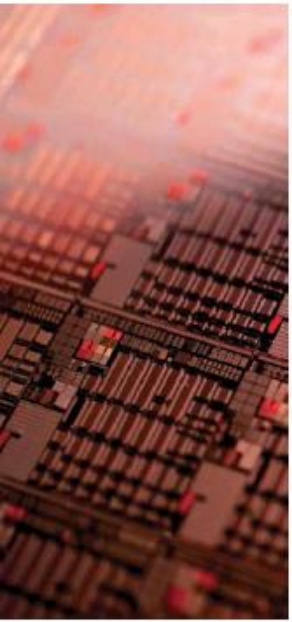
inorganic ↕ organic

Performance

- high spatial resolution for both organic and inorganic materials required
- metrology of 3D-heterogeneous systems
- high-resolution chemical identification
- Quantification and precision

Q&A MADE TO MEASURE – A LIFE OF METROLOGY

Innovation in semiconductor technology is dependent on metrology. The work of Professor Wilfried Vandervorst, Senior Fellow and Department Director of Materials and Components Analysis at Imec, in Belgium, has been instrumental to processing developments. Ledetta Asfa-Wossen takes a look at his career in research.



WHAT LED YOU TO ENTER THE FIELD OF METROLOGY?

I became interested in metrology for the semiconductor industry because physical analysis is such a mission-critical operation for the development of semiconductor technology. Once I was aware of the needs of this industry, I began to focus my research on metrology concepts for improved composition (surface, thin films) and impurity analysis (dopants, carriers). It's such a rapidly evolving field that requires a high degree of creativity, innovation and a permanent insight. I guess I took it as an opportunity to differentiate myself and to demonstrate my competencies and visions in various disciplines, such as engineering, physics and materials science.

WHAT EXCITED YOU ABOUT THE SUBJECT?

During my PhD project, I focused on the underlying physics of secondary ion mass spectrometry (SIMS) and electrical properties of point contacts. Through that I started to examine the metrological aspects, such as accuracy, quantification, and sensitivity and application value.

The excitement came when I was able to tell process and device engineers what they were making instead of what they thought they were making. The bridging of observing metrology and then linking the results to the fundamentals of processing really excited me. My job ranges from fundamental physics to practical instrument engineering and technological applications. I get to explore a wide range of metrology and fields in many different disciplines, from ion-solid interactions, electrical measurements and laser-solid interactions to process technology and instrument design. No two days are ever the same.

WHY IS METROLOGY SO CRUCIAL TO THE FABRICATION OF SEMICONDUCTORS?

Metrology is a great enabler. The fundamental insight created by metrology is key in accelerating R&D in process technology. Within the fabrication area, certifying that process tools behave the way they should and stay within their operational window represents an important tool for yield and production efficiency. Understanding the potential role of excursions is also crucial to the time window if yield ramping. There are vast economic benefits for conducting metrology too, specifically in the characterisation of nanoelectronics.

YOU PIONEERED DEVICE CHARACTERISATION USING SCANNING SPREADING RESISTANCE MICROSCOPY (SSRM). WHAT WAS NOVEL ABOUT THIS METHOD?

SSRM is the sole method we have for providing carrier profiles with adequate spatial resolution (<1nm) and sensitivity and quantification accuracy. Its uniqueness is the combination of all these properties. At the heart of every transistor lies a complex, engineered, electrically active dopant distribution controlling its electrical performance. As technology progresses, being able to create and control this distribution on the sub-nanometre scale becomes the key to successful device development. SSRM probes the spatial extent of the carrier distribution with nanometre resolution, thereby providing the essential feedback on the dopant incorporation and activation processes used to engineer modern devices.

WHAT DIRECT APPLICATION DID THE WORK HAVE?

When developing SSRM, 2D-profiling was listed as a red brick wall in The International Technology Roadmap for Semiconductors. Our developments removed this deficiency and, essentially, the wall.

WHAT WOULD YOU SAY IS YOUR GREATEST ACHIEVEMENT SO FAR?

Bringing SSRM from an initial idea to the commercial product market by addressing the fundamental physics as well as the engineering problems, from tips instrument to standards. SSRM is accessible to any user and it is being embraced by all major semiconductor companies, such as Intel, IBM, TSMC and Toshiba.

HOW WOULD YOU SAY METROLOGY IN THIS AREA HAS EVOLVED OVER THE LAST 10 YEARS?

Scanning probe microscopy has become routine, transmission electron microscopy (TEM) – a commodity and secondary ion mass spectrometry now a trustworthy, standard approach. Equally, advanced physical and electrical metrology has moved from blanket film and lab analysis towards fab and device analysis. We are also seeing advanced metrology transition from a single experiment and expert-based approach in the R&D phase towards high-volume, easily accessible support in the fab. Obviously, this creates a stronger return on investment by improving productivity and yield ramp, but it also means a more time-critical operation with tighter tolerances on accuracy and reproducibility.

ARE THERE ANY HINDRANCES TO METROLOGY INNOVATION?

The pure lack of dedicated funding opportunities for the science of metrology is an issue. The long development time to build and explore new instrumentation requires financial support that is sustained over many years prior to reaching the expected results. Nowadays, you also need very expensive instrumentation, which often exceeds standard budgets of funding agencies. A TEM or atom probe can cost £1.6–2.4m and it is hard for any researcher to get that kind of money solely for fundamental studies on how to improve metrology concepts.

WHY IS IT DIFFICULT TO SECURE FUNDING FOR METROLOGY COMPARED TO OTHER MATERIAL SCIENCE FIELDS?

Many reviewers do not appreciate the value of exploring the science and physics of metrology and its

Materials World, Januari 2015

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W.VANDERVORST

imec

WHAT MAKES A GOOD PROPOSAL?

Recent call : 3 submitted, 1 granted

- **Atom Probe Tomography (APT) Metrology for future 3D semiconductor devices (selected)**
- High resolution ion scattering characterization of nanostructures with Magnetic Analyzer and Silicon Strip detector.
- Low-temperature diamond nanoelectrodes for nanoelectronics device fabrication

ATOM PROBE TOMOGRAPHY (APT) METROLOGY FOR FUTURE 3D SEMICONDUCTOR DEVICES

Candidate : dr R.Morris, Univ Warwick, UK

- 13 years experience in semiconductor metrology research, in particular SIMS
- Publications : 60, h-index = 10
- Host : Imec = Largest research institute in semiconductors with extensive industrial partnerships. Extensive expertise in metrology for semiconductors.
- Content : Establish quantitative metrology with APT for 3D-devices
  - *Build on SIMS expertise*
  - *Explore fundamental physics of APT*
  - *Study industrially relevant applications for next generation technology nodes*
- Output *: Fundamental Understanding leading to Metrology protocols to be used in industry*
- Needs addressed *:*
  - *APT is emerging technology with lack of understanding and multiple artefacts limiting application on real industrially relevant devices. Create enhanced fundamental insight in APT.*
  - *APT is successor of SIMS (present standard) for industry : creating experts mastering both concepts alleviates industrial requirements*
  - *Create long term career perspective for Fellow by engaging in emerging technology*

HIGH RESOLUTION ION SCATTERING CHARACTERIZATION OF NANOSTRUCTURES WITH MAGNETIC ANALYZER AND STRIP DETECTOR

Candidate : Dr. Andrzejewski , (Madrid, Riken-Japan, Poland, Luxemburg)

- 7 years experience in instrument design and construction for ion beam analysis
- Publications :8 ,
- Host : Imec = Largest research institute in semiconductors with extensive industrial partnerships. Extensive expertise in metrology for semiconductors.
- Content : Create high resolution IBA using a novel dectector design . targeting analysis of nanostructures
  - *Build on expertise of Fellow to design and implement novel detector*
  - *Explore fundamental performance of system*
  - *Study industrially relevant applications for next generation technology nodes*
- Output *: IBA system with high depth resolution capabilities to be used in next technologiy nodes*
- Needs addressed *:*
  - *IBA is attractive because of its quantification but suffers from poor depth resolution due to detector limitations*
  - *Novel segmented detector may overcome these limitations. No commercial system available.*
  - *Prepare IBA for next generation technologies*

LOW-TEMPERATURE DIAMOND NANOELECTRODES FOR NANOELECTRONICS DEVICE FABRICATION

Candidate :dr E. Skotadis, Greece

- 3 years experience in nanoparticle and sensors
- Publications :7 ,
- Host : Imec = Largest research institute in semiconductors with extensive industrial partnerships. Extensive expertise in metrology for semiconductors.

Content : Low-temperature diamond nanoelectrodes for nanoelectronics device fabrication"

- *Build on expertise of Fellow to manipulate nanoparticiles (for diamond seeding)*
- *Create boron doped diamond seeding*
- *Fundamentals of low temperature diamond growth*

- Output *: process technology for the implementation of inert conductive electrodes above IC*
- Needs addressed *: conductive diamond films above IC as sensors, electrodes in medical devices,*
  - *low-temperature growth at <500° C,*
  - *seeding with Boron doped diamond nanoparticles.*

	Atomprobe for 3D device	**Low temp doped diamond**	**High resolution ion scattering**
Total score	93.4	87.2	83.4
excellence	4.7	4.6	4.4
impact	4.6	4.2	4.4
implementation	4.7	4.2	4.2
Fellow after PhD	15 years PhD	1 years	7 years
publications	60	5	8
Building on Experience in topic	SIMS vs APT	Related (Nanoparticle)	Yes (IBA and instrument design)

Common weakness

- Quantitative impact on career.
- Hosting details
- Specific public engagement actions
- Risk mitigation

Excellence

Quality, innovative aspects and credibility of the research (including inter/multidisciplinary aspects).

Proposal content

- Atomprobe is the emerging 3D-technology considered to be complement of SIMS.
- Application to semiconductors requires a lot of innovative solutions (listed problems and route towards improvements)
- Building on the skills of the fellow (expert in metrology and SIMS) and host (SIMS, atomprobe) to establish credibility that project can succeed.
- Project will be based on multiple disciplines (SIMS, APT, Laser-nano-object interaction, simulations,...)

Reviewers response :

The research objectives are convincingly outlined against the state of the art and their importance is clearly described.

-The project is innovative and the research is timely.

-The proposed research programme has interdisciplinary and multidisciplinary aspects.

Excellence

- **Clarity and quality of transfer of knowledge/training for the development of researcher in light of the research objectives.**
- **Quality of the supervision and the hosting arrangements**

Transfer-of-knowledge objectives closely match the project work packages.

- *The host offers complementary skill training.*
    - *Imec Academy (technical, soft skills, management), KULeuven*
- *The supervisor and the host institute have excellent scientific records.*
    - *Imec is recognized as center of excellence for semiconductor research*
    - *Host (WVDV) = Senior Imec Fellow and recognized word authority in metrology (SIMS, ATP, SPM,...)*
- *The host offers unique characterization facilities essential to this project.*
    - *Extensive complementary metrology tools (TEM, SIMS, SPM,ATP,...) and fabrication facilities (EUV, advanced processing,..)*
- *The fellow has shown exceptional scientific activity during his career.*
    - *Fellow is recognized authority in SIMS field (15 years) and developed extensive complementary expertise*
- *The fellow has been involved in international research collaborations.*
    - *Fellow has been involved in multiple intern. interactions, fund raising*

Weaknesses:

- *The proposal fails to describe the hosting arrangements in sufficient detail.*
    - *No idea what they want to see more...*

EXCELLENCE

Score: **4.70** (**Weight: 50.00%, REALLY important**)

- Topic has to be scientifically relevant and embedded in innovative strategy.
- Build on your own expertise and infrastructure towards scientific excellence in the proposal.
- It helps to have a well established candidate.
- Hosting facilities (technical, training) are important, need proper documentation.

IMPACT : Score: **4.60** (Weight: 30.00%)

Enhancing research- and innovation-related human resources, skills, and working conditions to realise the potential of individuals and to provide new career perspectives

Effectiveness of the proposed measures for communication and results dissemination

Strengths:

- *The proposal describes how the project will enhance the skills of the applicant. The potential benefits for the European Research Area in the field of the emerging techniques are addressed in the project.*
- *The fellow will become an expert in an emerging new characterization technology.*
    - *Present expertise SIMS : after training he will become also an APT expert which is the next generation SIMS*
- *The novel technology to be developed will expose the fellow to close collaboration with industry.*
    - *APT is rapidly finding applications in semiconductor industry*
    - *Education in APT makes Fellow ready for next generation technology.*

- The fellow has previous practical experience in outreach activities to promote physics.

- *The dissemination plan includes also the communication of research results to industry.*
    - *Employing all dissemination channels of Imec (PTW, ITF, magazine,) + regular papers, conf,...and outreach activities of Fellow*
- *Intellectual property rights issues and rapid commercial exploitation of the results are well integrated in the project.*
    - *Building on Strong Imec IP policy*

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IMPACT : SCORE: 4.60 (WEIGHT: 30.00)

Weaknesses:

- *The specific planned activities for dissemination are inadequately described.*
  - *Activities were only described in general terms*
  - *??how to improve?*

- *New career perspectives for the fellow generated by the project are not clearly described*
  - *The acquisition of the APT skills should open multiple prospects as APT is becoming more widespread with a lack of qualified staff.*
  - *We did not (hard to do) give solid evidence of potential positions he would get after three years (1 year proposal, 2 year fellowship..).*

Implementation : Score: **4.70 (**Weight: 20.00%)

Overall coherence and effectiveness of the work plan, including appropriateness of the allocation of tasks and resources
Appropriateness of the management structures and procedures, including quality management and risk management
Appropriateness of the institutional environment (infrastructure)
Competences, experience and complementarity of the participating organisations and institutional commitment

Strengths:
- The work plan is detailed and in line with the project objectives.
- Outreach activities have been integrated into the work plan.
- The management of the project has been planned in a convincing way; a career development strategy is in place and periodic evaluation meetings have been planned.
- Risks have been assessed.
- The host has outstanding infrastructure which matches perfectly with this project.
- The research environment is very stimulating and international.
- The host and collaborating industrial partners are experienced and collaboration with them will certainly be beneficial to the fellow.

Weaknesses :
- Risk mitigation is not adequately addressed.

Recurring weakness statement for all three proposals

- Quantitative impact on future career.
  - *Very hard to make solid statement three years in advance*
  - *General terms were given*

- Hosting details
  - *With ~350 industrial assignees and post-docs at Imec we take hosting as a non-issue. Reviewers clearly have not the same experience and want more (which?) details.*

- Specific public engagement actions
  - *We referred to imec's public actions : ITF, PTW, Magazine, etc..*
  - *? What are the reviewers looking for?*

- *Risk mitigation*

RISK MITIGATION (NOT GOOD ENOUGH)

Risks that might endanger the project objectives.

Some of the potential risks to the project and their contingencies include:

- **Risk:** Failure to obtain any tip yield.

  Contingency: Explore oxide removal by etching, use model systems (modified process flow at Imec) to demonstrate 3D-device analysis capability without the oxide problem.

- **Risk:** Failure to localize device of interest below cap layer; **Contingency:** Abandon site specific analysis and stay with arrays of devices.

- **Risk:** Failure to develop model description:

  Contingency: Experimental observation can still lead to phenomena logical optimized procedure.

- **Risk** :Failure to achieve reliable reconstruction.

  Contingency : If proven untractable, the work will still provide valauble information and clear guidelines on where (not) to trust APT results

Risk mitigation (not good enough)

- *Risk*: boron doped diamond nanoparticles with lower conductivity when anticipated by cost-efficient HPHT;

  Contingency: switch to CVD boron doped diamond with high doping capabilities.

- *Risk*: Low-temperature (≤500°C) diamond layer with lower conductivity when expected;

  Contingency: HVCVD and LACVD are explored in parallel; increases chances for success; if all fails, move to 500-550°C.

- Risk: Model fails to precisely predict the interfacial resistance of fully conductive BDD layers;

  Contingency: use extra experimental observation/characterization for fine-tuning model; proceed further with limited model.

- Risk: Integrated diamond process (≤500°C) for neural probes is failing;
  Contingency: move to 500-550°C, proceed with non-integrated diamond structures which allows for benchmarking against metal-oxide electrodes.

IMPLEMENTATION SCORE

Strengths

- GANTT and clear organization into WP,
- Adequate deliverables
- Infrastructure
- Meeting schedules

Differentiatiors (?) 4.7 vs 4.2

- Clearer, quantitative deliverables
- Career plan for Fellow
- Interaction with industrial partners

IMPACT SCORING

Strengths

Broadening of Fellow expertise and skills

IP is integrated

Match host experience and proposed research

Differentiator(4.6 vs 4.2)

Outreach activities of Fellow and Host

Link to industry

The host has outstanding infrastructure which matches perfectly with this project.
- The research environment is very stimulating and international.
- The host and collaborating industrial partners are experienced and collaboration with them will certainly be beneficial to the fellow.

- Build on your strengths
- Build on your institute
- Build on your expertise
- Build on your industrial partnerships

GENERAL COMMENTS

Write proposal with the list of questions to the reviewers in mind.

Create transparent answer to ALL questions

- Excellence
- Impact
- Implementation

YOU NEED SOME STATISTICAL LUCK WITH REVIEWERS.

Prop 2 :Weakness : There is no program of formal technical training **4.4**

- Acquiring experimental experience by hands on training in operating the high-energy accelerator and the various experimental end-stations at imec. It is the aim that, through daily experience, the researcher will be able to supervise and lead an accelerator lab independently. (WP1)
- - Acquiring a fundamental understanding of the underlying physics of charge exchange processes upon medium energy ion scattering (WP4)
- - Establishing proficiency in optimized data analysis based on acquired insight into the physics of the two-dimensional energy/position spectra through intense collaboration with the imec researchers (WP4)

- Establishing proficiency in coincidence data mining processes to optimize the extraction of information (WP4)
- - Establishing proficiency in leading and organizing a major project of development. (WP2)
- - The researcher will (re-)establish a solid network of collaboration in the ion beam analysis community (WP2). The researcher will also be exposed to the needs and the dynamics of the micro-electronics research community.
- be exposed to the way-of-working in an industrial

Prop 1 Strengths : Transfer-of-knowledge objectives closely match the project work packages. **4.7**

- *Building experimental experience by hands on training in site selective sample preparation and tip shaping based on FIB, (WP1)*
- *Acquiring a fundamental knowledge related to the underlying physics of the laser assisted evaporation process by working alongside imec's APT-team and its theoreticians (WP2)*
- *Establishing proficiency in optimized data generation based on acquired insight into the physics of the tip shape evolution and the parameters controlling it (WP3)*

- *Establishing proficiency in correlative data reconstruction (APT-TEM tomography) through interaction with Imec and its collaborators. (WP4)*

- *Acquire knowledge of advanced technology from device engineers through case studies linking APT-results with device development (WP 5)*