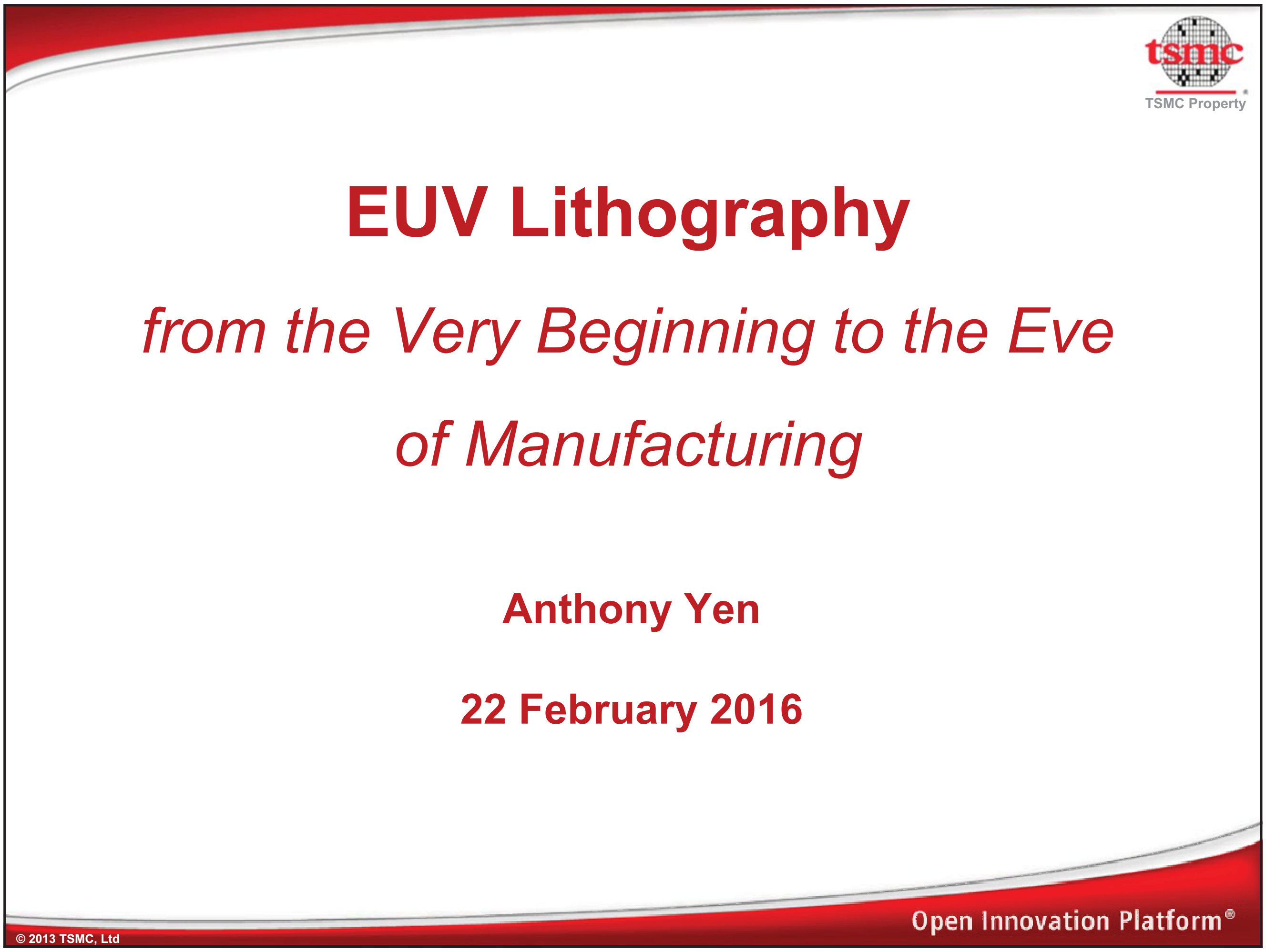


TSMC Property

EUV Lithography

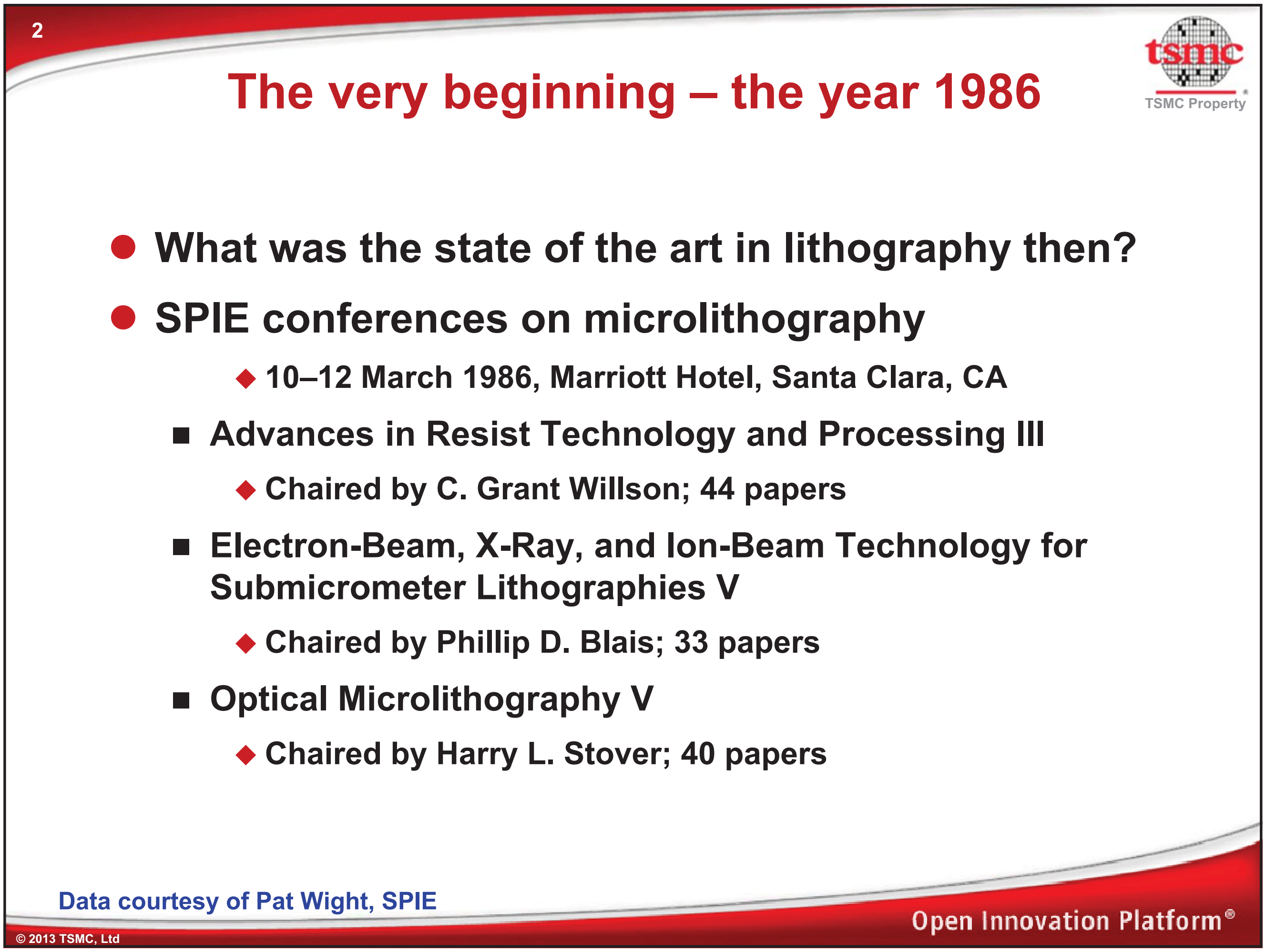
from the Very Beginning to the Eve of Manufacturing

Anthony Yen

22 February 2016

Open Innovation Platform®

Extreme Ultraviolet (EUV) Lithography VII, edited by Eric M. Panning, Kenneth A. Goldberg. Proc. of SPIE Vol. 9776, 977632 · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2236044



The very beginning – the year 1986

- What was the state of the art in lithography then?
- SPIE conferences on microlithography
    - ◆ 10–12 March 1986, Marriott Hotel, Santa Clara, CA
  - ■ Advances in Resist Technology and Processing III
    - ◆ Chaired by C. Grant Willson; 44 papers
  - ■ Electron-Beam, X-Ray, and Ion-Beam Technology for Submicrometer Lithographies V
    - ◆ Chaired by Phillip D. Blais; 33 papers
  - ■ Optical Microlithography V
    - ◆ Chaired by Harry L. Stover; 40 papers

Data courtesy of Pat Wight, SPIE

First few papers in Optical Microlithography V

A Glimpse Into The Future Of Optical Lithography PDF
Harry L. Stover
Proc. SPIE 0633, Optical Microlithography V, 2 (August 20, 1986); doi: 10.1117/12.963696

Excimer Laser-Based Lithography: A Deep Ultraviolet Wafer Stepper PDF
Victor Pol, James H. Bennewitz, Gary C. Escher, Martin Feldman, Victor A. Firtion, Tanya E. Jewell, Bruce E. Wilcomb, James T. Clemens
Proc. SPIE 0633, Optical Microlithography V, 6 (August 20, 1986); doi: 10.1117/12.963697

New Projection Lenses For Optical Stepper PDF
Kazuo Ushida, Masaomi Kameyama, Satoru Anzai
Proc. SPIE 0633, Optical Microlithography V, 17 (August 20, 1986); doi: 10.1117/12.963698

Practical I-Line Lithography PDF
Mike Tipton, Vic Marriott, Gene Fuller
Proc. SPIE 0633, Optical Microlithography V, 24 (August 20, 1986); doi: 10.1117/12.963699

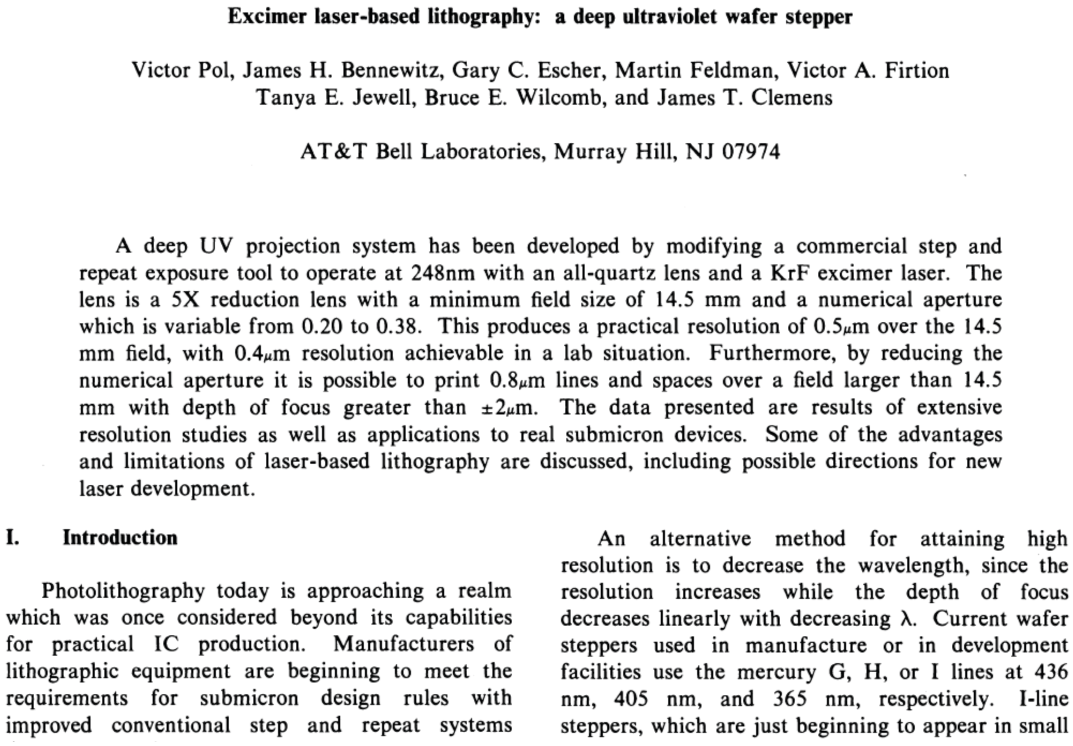
A New Lens For Submicron Lithography And Its Consequences For Wafer Stepper Design PDF
J. Biesterbos, A. Bouwer, G. V. Engelen, G . V. D. Looij, J. V. D. Werf
Proc. SPIE 0633, Optical Microlithography V, 34 (August 20, 1986); doi: 10.1117/12.963700

Where Is The Lost Resolution? PDF
Burn J. Lin
Proc. SPIE 0633, Optical Microlithography V, 44 (August 20, 1986); doi: 10.1117/12.963701

Excimer Laser Projection Patterning With And Without Resists: Submicrometer Etching Of Diamond And Diamond-Like Carbon Resist PDF
M. Rothschild, C. Arnonet, D. J. Ehrlich
Proc. SPIE 0633, Optical Microlithography V, 51 (August 20, 1986); doi: 10.1117/12.963702

Direct-Referencing Automatic Two-Points Reticle-To-Wafer Alignment Using A Projection Column Servo System PDF
M. A. v. d. Brink, H. F. D. Linders, S. Wittekoek
Proc. SPIE 0633, Optical Microlithography V, 60 (August 20, 1986); doi: 10.1117/12.963703

The Victor Pol paper - first 248-nm wafer stepper



Excimer laser-based lithography: a deep ultraviolet wafer stepper

Victor Pol, James H. Bennewitz, Gary C. Escher, Martin Feldman, Victor A. Firtion
Tanya E. Jewell, Bruce E. Wilcomb, and James T. Clemens

AT&T Bell Laboratories, Murray Hill, NJ 07974

A deep UV projection system has been developed by modifying a commercial step and repeat exposure tool to operate at 248nm with an all-quartz lens and a KrF excimer laser. The lens is a 5X reduction lens with a minimum field size of 14.5 mm and a numerical aperture which is variable from 0.20 to 0.38. This produces a practical resolution of 0.5μm over the 14.5 mm field, with 0.4μm resolution achievable in a lab situation. Furthermore, by reducing the numerical aperture it is possible to print 0.8μm lines and spaces over a field larger than 14.5 mm with depth of focus greater than ±2μm. The data presented are results of extensive resolution studies as well as applications to real submicron devices. Some of the advantages and limitations of laser-based lithography are discussed, including possible directions for new laser development.

I. Introduction

Photolithography today is approaching a realm which was once considered beyond its capabilities for practical IC production. Manufacturers of lithographic equipment are beginning to meet the requirements for submicron design rules with improved conventional step and repeat systems

An alternative method for attaining high resolution is to decrease the wavelength, since the resolution increases while the depth of focus decreases linearly with decreasing λ. Current wafer steppers used in manufacture or in development facilities use the mercury G, H, or I lines at 436 nm, 405 nm, and 365 nm, respectively. I-line steppers, which are just beginning to appear in small

Proc. SPIE 0633, 6 (1986)

And what did the conference chair have to say?

CHAIRMAN'S OVERVIEW

"A Glimpse into the Future of Optical Lithography"

Harry L. Stover
ASM Lithography
Veldhoven, The Netherlands

ABSTRACT

The conference papers relating to resolution and overlay of exploratory but production-worthy exposure/alignment systems indicate performance far exceeding current IC manufacturing demands, and hence give a glimpse of future production systems and design rules. A summary table is presented.

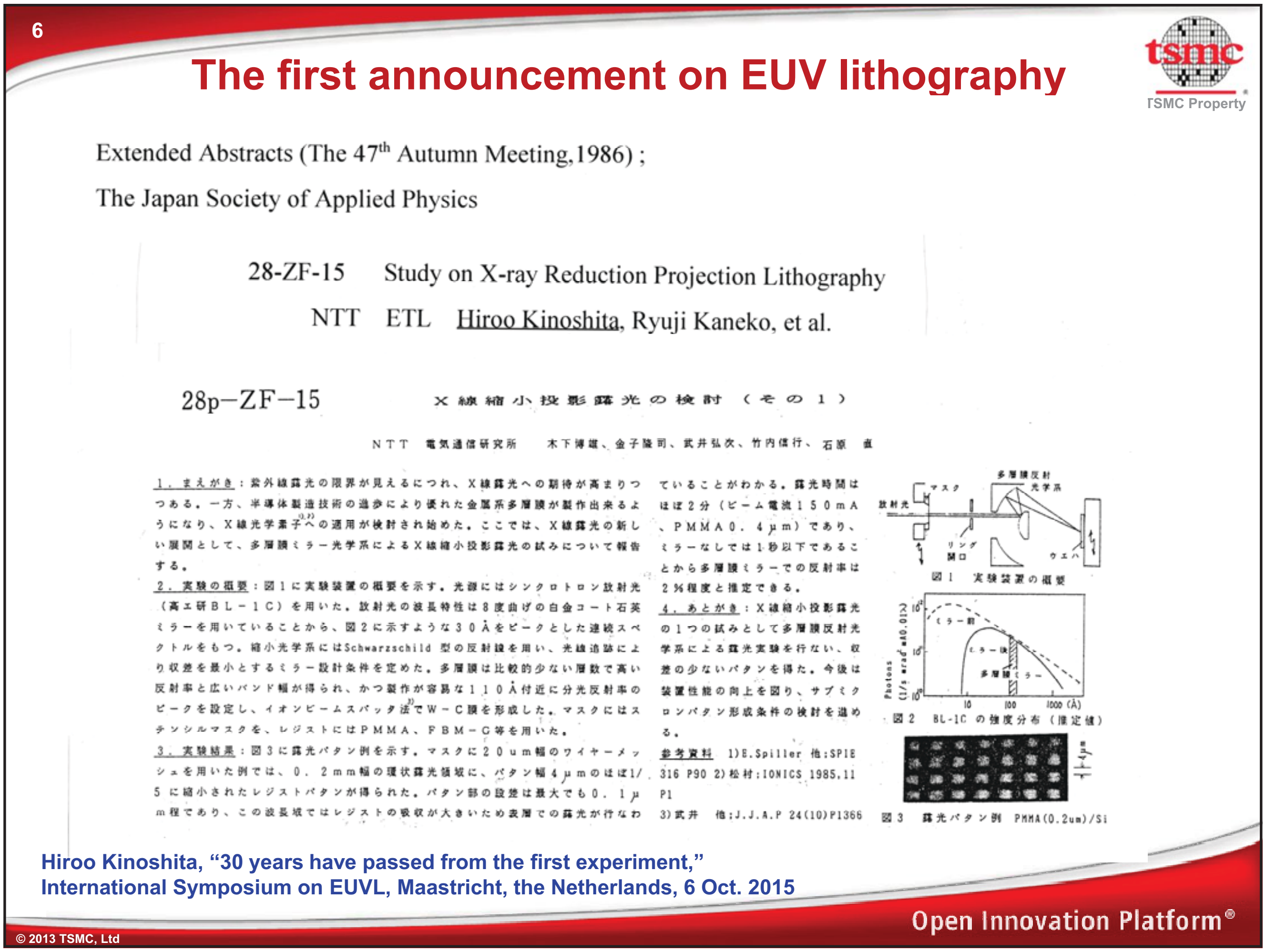
and the paper's final paragraphs:

Meaning: What do all these impressive developments mean to users and to the competitive lithographic technologies ? Well, there is good news and there is bad news ! The good news, to chip manufacturers, is that they can sleep easier tonight, knowing that they can count on optical microlithography to continue the gradual but stable evolution that has given ever-increasing productivity, - unprecendented in history, to the microelectronic industry. (They can now devote their waking energies to creating new chip demand, to pull the industry out of this recession).

The bad news, to the competing replication technologies such as X-ray and flood ion-beam systems, is that they can still expect a very long bridesmaid wait by the telephone before they will be called upon to fill a void in high-volume IC manufacturing left by optical microlithography.

I thank all of you for your extraordinary response, in quantity and quality of papers, and in your attendance to the Fifth Annual SPIE Conference on Optical Microlithography.

Proc. SPIE 0633, 3 (1986)



The first announcement on EUV lithography

Extended Abstracts (The 47th Autumn Meeting,1986) ;
The Japan Society of Applied Physics

28-ZF-15 Study on X-ray Reduction Projection Lithography
NTT ETL Hiroo Kinoshita, Ryuji Kaneko, et al.

28p−ZF−15 X線縮小投影露光の検討（その１）

ＮＴＴ 電気通信研究所 木下博雄、金子隆司、武井弘次、竹内信行、石原 直

1．まえがき：紫外線露光の限界が見えるにつれ、Ｘ線露光への期待が高まりつつある。一方、半導体製造技術の進歩により優れた金属系多層膜が製作出来るようになり、Ｘ線光学素子[1,2]への適用が検討され始めた。ここでは、Ｘ線露光の新しい展開として、多層膜ミラー光学系によるＸ線縮小投影露光の試みについて報告する。

2．実験の概要：図１に実験装置の概要を示す。光源にはシンクロトロン放射光（高エ研ＢＬ−１Ｃ）を用いた。放射光の波長特性は８度曲げの白金コート石英ミラーを用いていることから、図２に示すような３０Åをピークとした連続スペクトルをもつ。縮小光学系にはSchwarzschild 型の反射鏡を用い、光線追跡により収差を最小とするミラー設計条件を定めた。多層膜は比較的少ない層数で高い反射率と広いバンド幅が得られ、かつ製作が容易な１１０Å付近に分光反射率のピークを設定し、イオンビームスパッタ法[3]でＷ−Ｃ膜を形成した。マスクにはステンシルマスクを、レジストにはＰＭＭＡ、ＦＢＭ−Ｇ等を用いた。

3．実験結果：図３に露光パタン例を示す。マスクに２０ｕｍ幅のワイヤーメッシュを用いた例では、０．２ｍｍ幅の環状露光領域に、パタン幅４μｍのほぼ1/5 に縮小されたレジストパタンが得られた。パタン部の段差は最大でも０．１μｍ程であり、この波長域ではレジストの吸収が大きいため表層での露光が行なわていることがわかる。露光時間はほぼ２分（ビーム電流１５０ｍＡ、ＰＭＭＡ０．４μｍ）であり、ミラーなしでは１秒以下であることから多層膜ミラーでの反射率は２％程度と推定できる。

4．あとがき：Ｘ線縮小投影露光の１つの試みとして多層膜反射光学系による露光実験を行ない、収差の少ないパタンを得た。今後は装置性能の向上を図り、サブミクロンパタン形成条件の検討を進める。

参考資料 1)E.Spiller 他:SPIE 316 P90 2)松村:IONICS 1985.11 P1 3)武井 他:J.J.A.P 24(10)P1366

図１ 実験装置の概要

図２ BL-1C の強度分布（推定値）

図３ 露光パタン例 PMMA(0.2um)/Si

Hiroo Kinoshita, “30 years have passed from the first experiment,”
International Symposium on EUVL, Maastricht, the Netherlands, 6 Oct. 2015

Details of Kinoshita's setup and results

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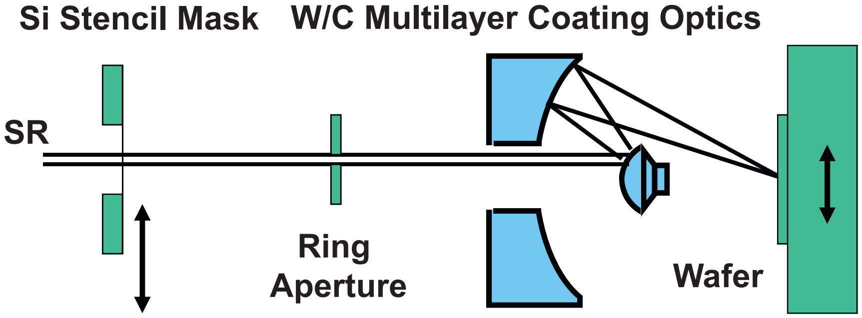


λ=11 nm, provided by synchrotron radiation

8X, ring-field Schwarzschild optics; exposure carried out by scanning mask and wafer

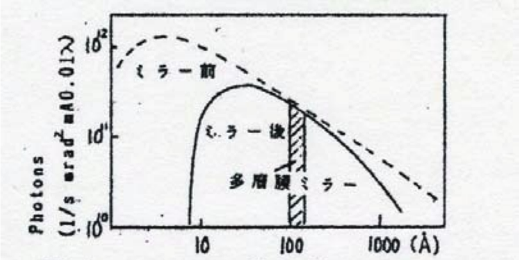


図 2　BL-1C の強度分布（推定値）

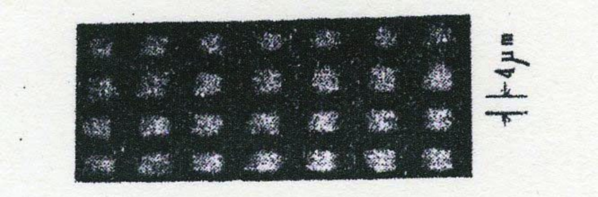
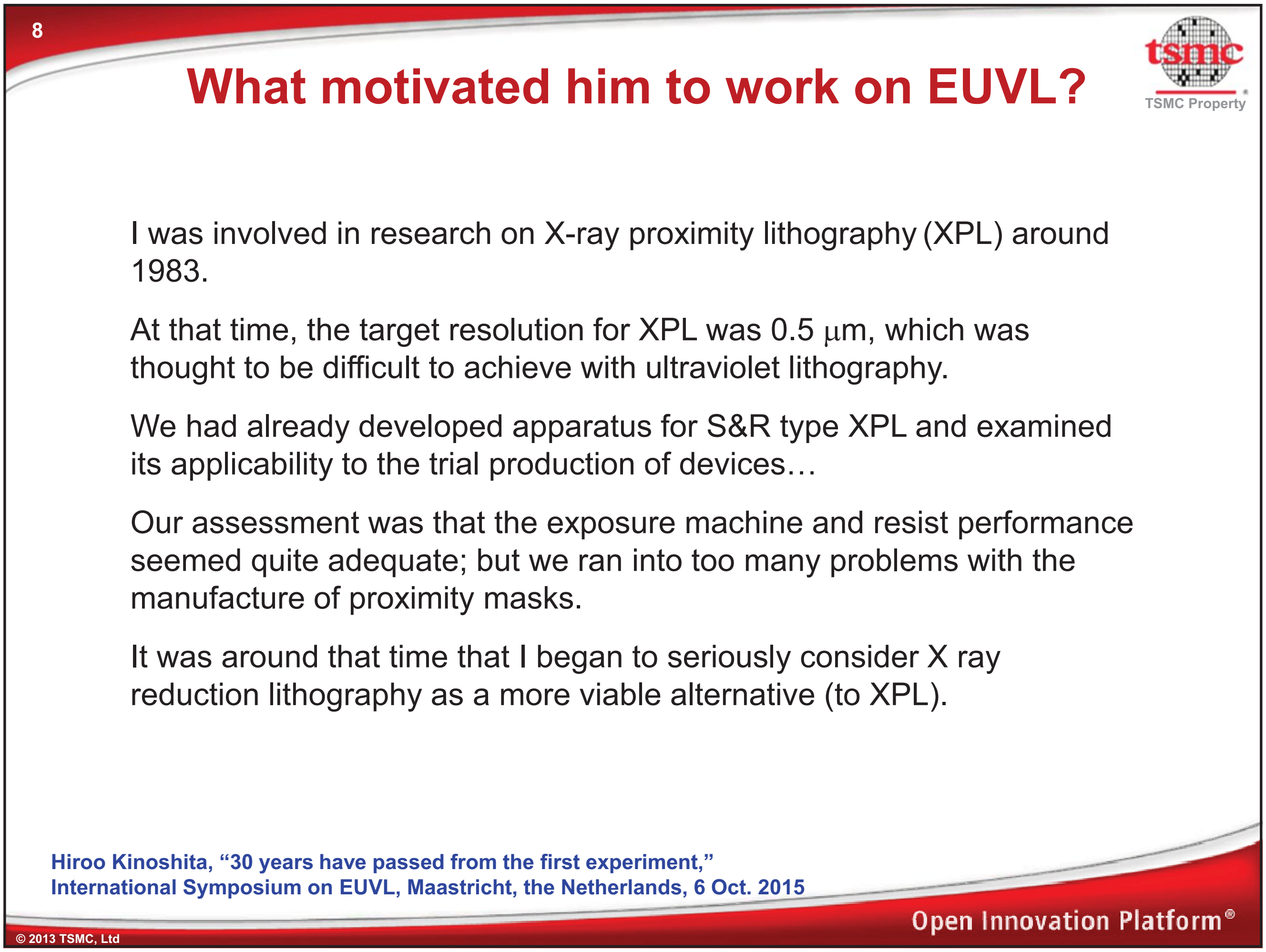


図 3　露光パタン例　PMMA(0.2um)/Si

Hiroo Kinoshita, "30 years have passed from the first experiment,"
International Symposium on EUVL, Maastricht, the Netherlands, 6 Oct. 2015



What motivated him to work on EUVL?

I was involved in research on X-ray proximity lithography (XPL) around 1983.

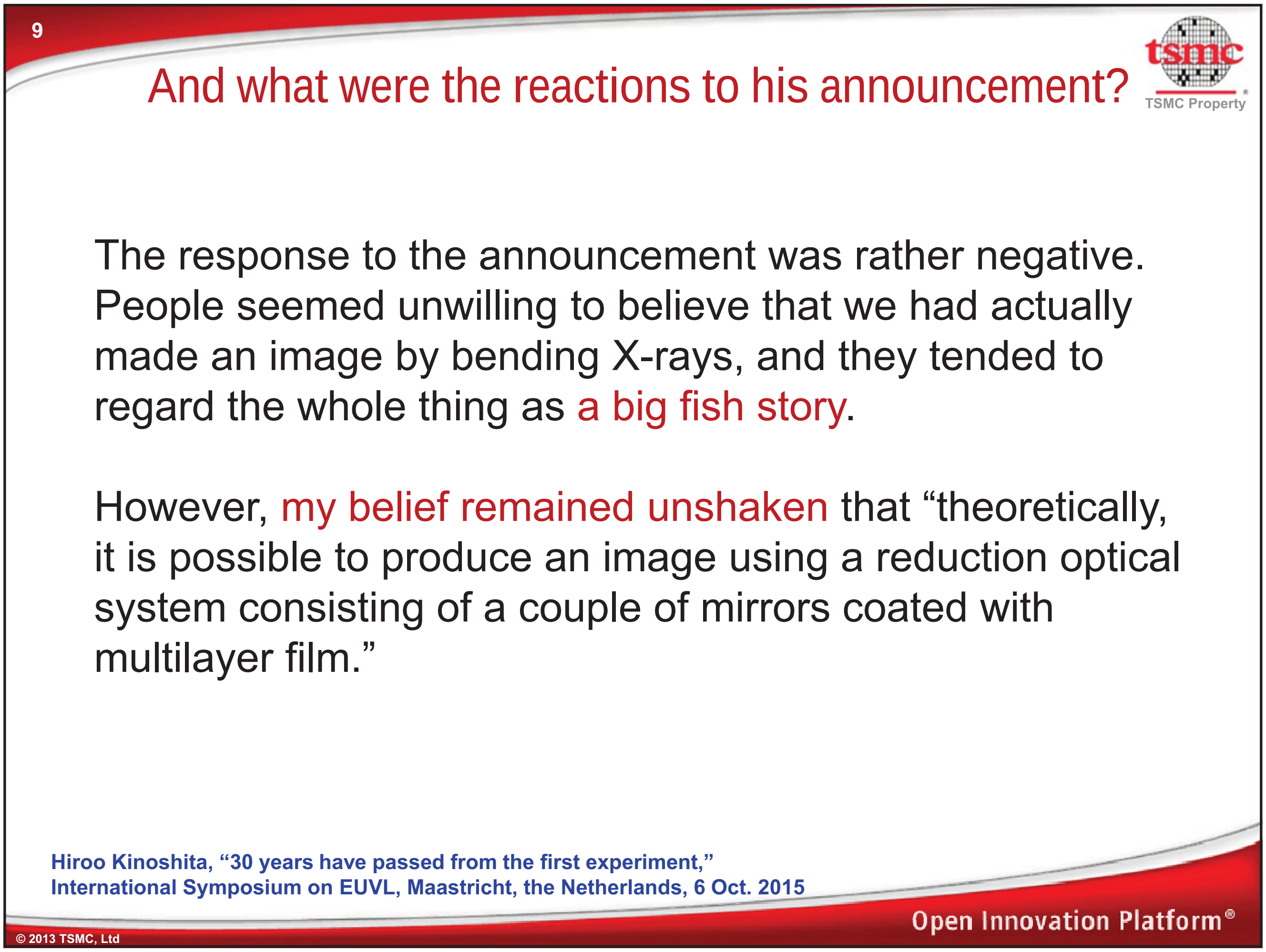
At that time, the target resolution for XPL was 0.5 μm, which was thought to be difficult to achieve with ultraviolet lithography.

We had already developed apparatus for S&R type XPL and examined its applicability to the trial production of devices…

Our assessment was that the exposure machine and resist performance seemed quite adequate; but we ran into too many problems with the manufacture of proximity masks.

It was around that time that I began to seriously consider X ray reduction lithography as a more viable alternative (to XPL).

Hiroo Kinoshita, "30 years have passed from the first experiment,"
International Symposium on EUVL, Maastricht, the Netherlands, 6 Oct. 2015

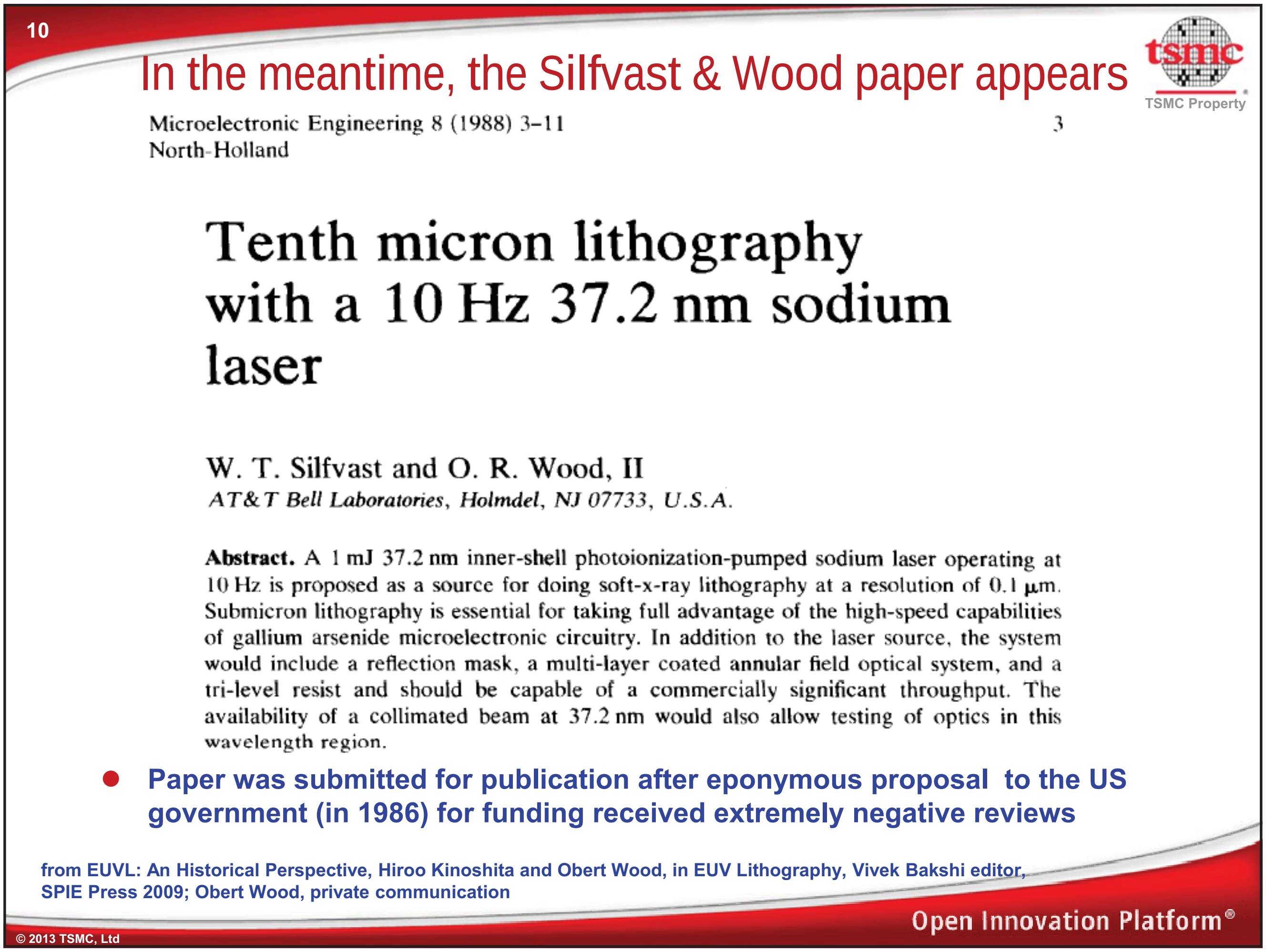


And what were the reactions to his announcement?

The response to the announcement was rather negative. People seemed unwilling to believe that we had actually made an image by bending X-rays, and they tended to regard the whole thing as a big fish story.

However, my belief remained unshaken that “theoretically, it is possible to produce an image using a reduction optical system consisting of a couple of mirrors coated with multilayer film.”

Hiroo Kinoshita, “30 years have passed from the first experiment,”
International Symposium on EUVL, Maastricht, the Netherlands, 6 Oct. 2015



In the meantime, the Silfvast & Wood paper appears

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Microelectronic Engineering 8 (1988) 3–11
North-Holland

Tenth micron lithography with a 10 Hz 37.2 nm sodium laser

W. T. Silfvast and O. R. Wood, II
AT&T Bell Laboratories, Holmdel, NJ 07733, U.S.A.

Abstract. A 1 mJ 37.2 nm inner-shell photoionization-pumped sodium laser operating at 10 Hz is proposed as a source for doing soft-x-ray lithography at a resolution of 0.1 μm. Submicron lithography is essential for taking full advantage of the high-speed capabilities of gallium arsenide microelectronic circuitry. In addition to the laser source, the system would include a reflection mask, a multi-layer coated annular field optical system, and a tri-level resist and should be capable of a commercially significant throughput. The availability of a collimated beam at 37.2 nm would also allow testing of optics in this wavelength region.

- **Paper was submitted for publication after eponymous proposal to the US government (in 1986) for funding received extremely negative reviews**

from EUVL: An Historical Perspective, Hiroo Kinoshita and Obert Wood, in EUV Lithography, Vivek Bakshi editor, SPIE Press 2009; Obert Wood, private communication

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The Silfvast & Wood Proposal for EUVL

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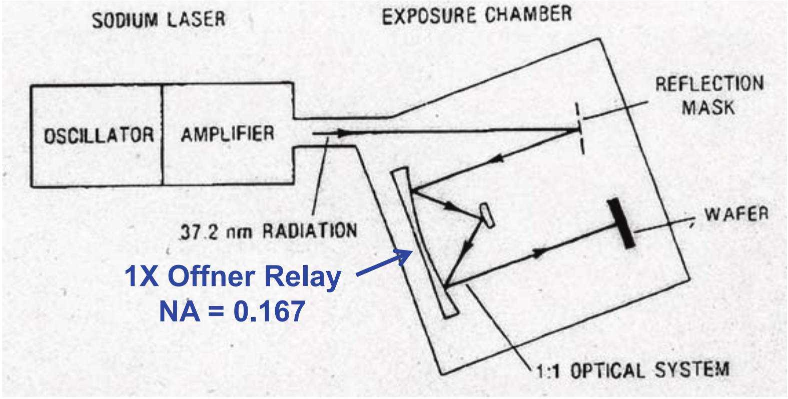
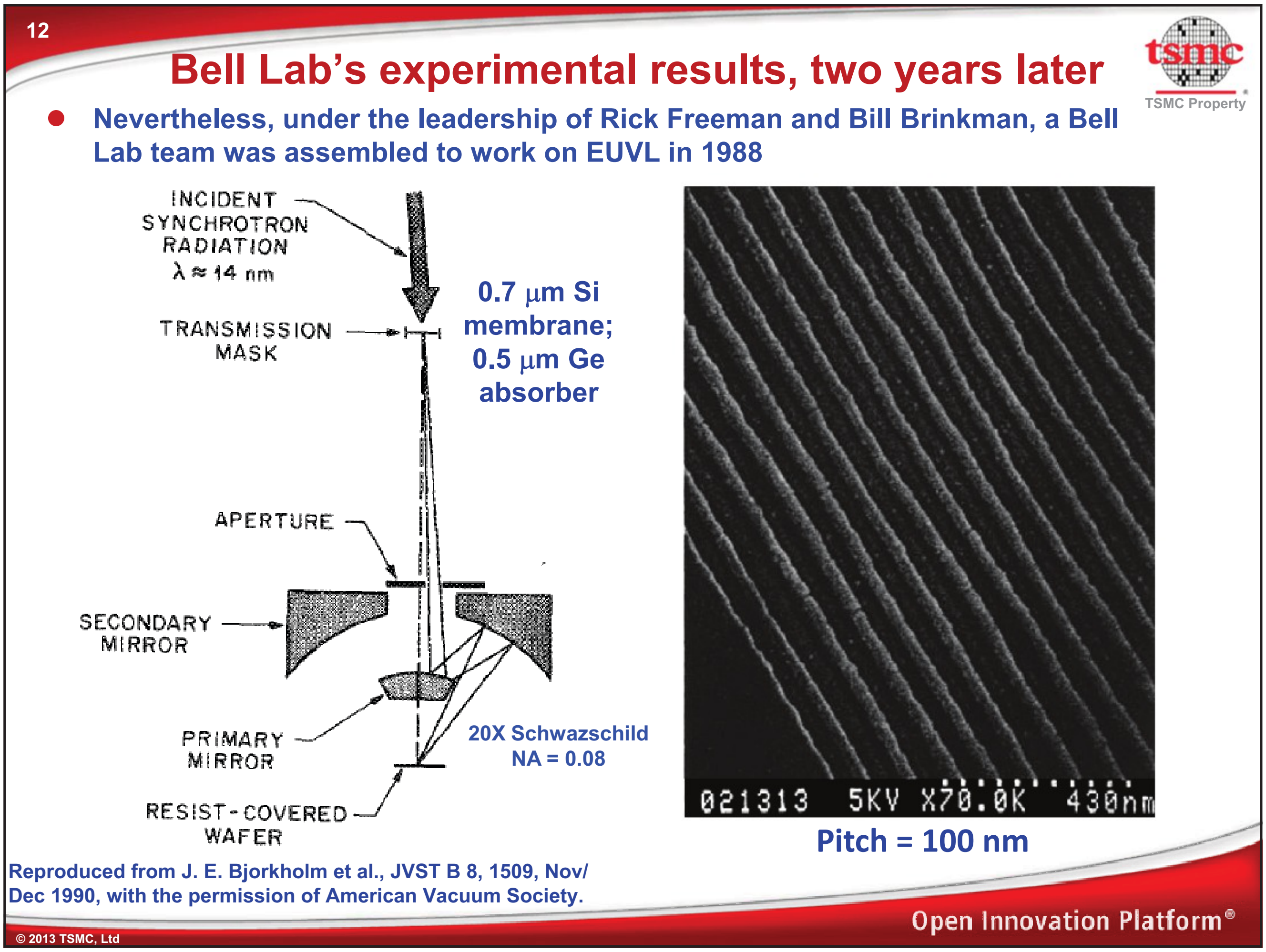


1X Offner Relay
NA = 0.167

- Use of reflective mask was mentioned
- Proposed Mg/Au or Mg/Pt MLs with 35% reflectivity at 37.2 nm

Photo courtesy of Obert Wood



Bell Lab's experimental results, two years later

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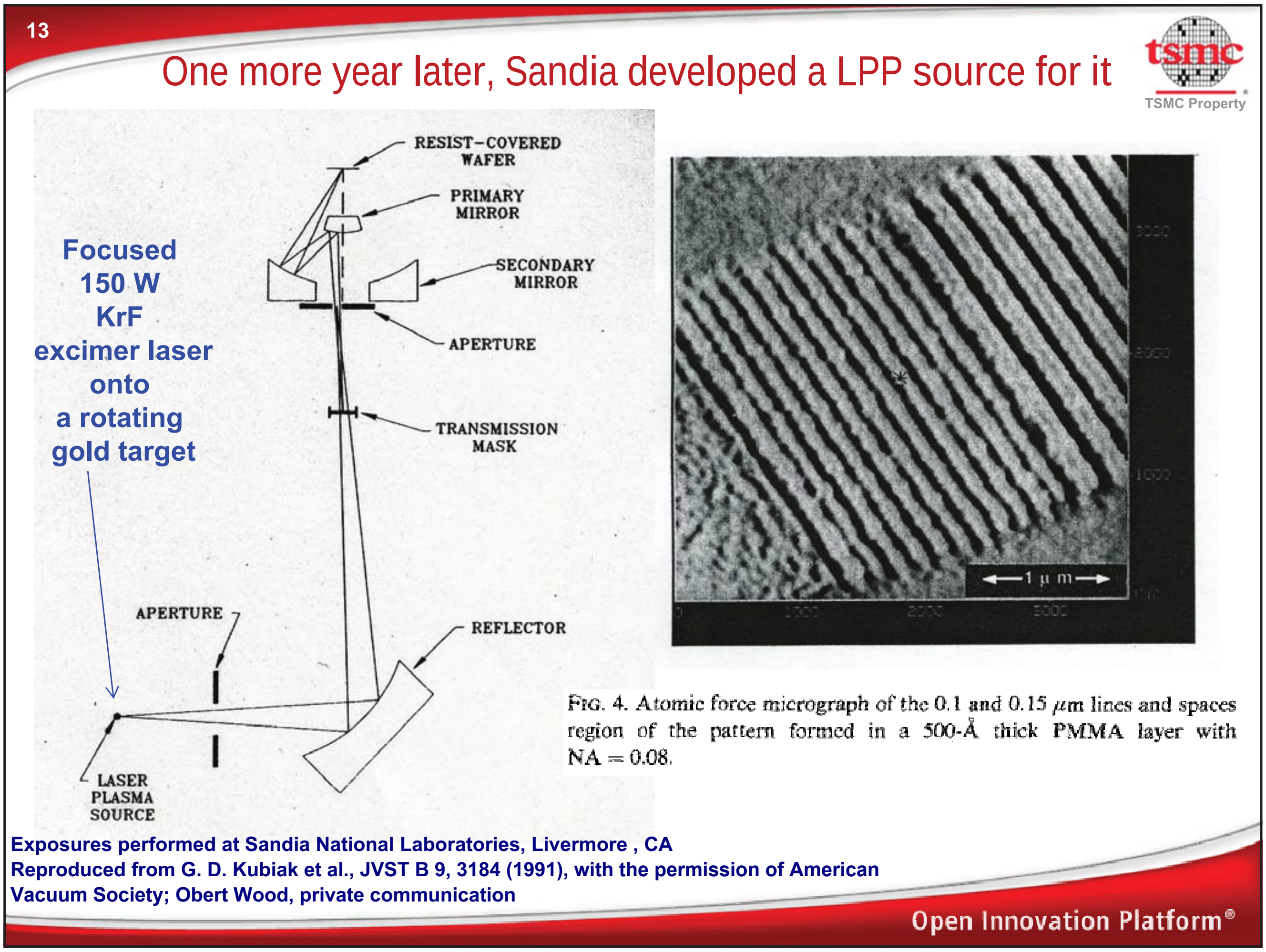
- **Nevertheless, under the leadership of Rick Freeman and Bill Brinkman, a Bell Lab team was assembled to work on EUVL in 1988**

0.7 μm Si membrane; 0.5 μm Ge absorber

20X Schwazschild
NA = 0.08

Pitch = 100 nm

Reproduced from J. E. Bjorkholm et al., JVST B 8, 1509, Nov/ Dec 1990, with the permission of American Vacuum Society.



One more year later, Sandia developed a LPP source for it

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Focused 150 W KrF excimer laser onto a rotating gold target

FIG. 4. Atomic force micrograph of the 0.1 and 0.15 μm lines and spaces region of the pattern formed in a 500-Å thick PMMA layer with NA = 0.08.

Exposures performed at Sandia National Laboratories, Livermore , CA
Reproduced from G. D. Kubiak et al., JVST B 9, 3184 (1991), with the permission of American Vacuum Society; Obert Wood, private communication

Independently, at 1988 3-beams conference in Ft. Lauderdale

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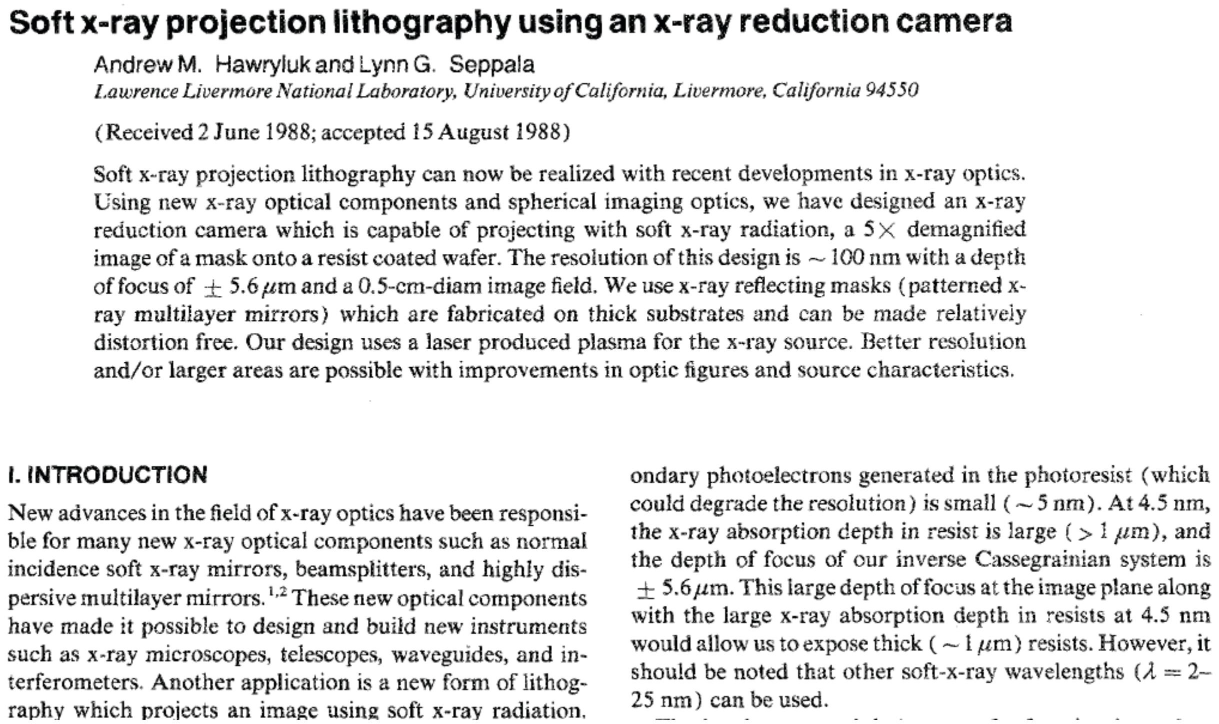

Soft x-ray projection lithography using an x-ray reduction camera

Andrew M. Hawryluk and Lynn G. Seppala
Lawrence Livermore National Laboratory, University of California, Livermore, California 94550

(Received 2 June 1988; accepted 15 August 1988)

Soft x-ray projection lithography can now be realized with recent developments in x-ray optics. Using new x-ray optical components and spherical imaging optics, we have designed an x-ray reduction camera which is capable of projecting with soft x-ray radiation, a 5× demagnified image of a mask onto a resist coated wafer. The resolution of this design is ~100 nm with a depth of focus of ±5.6 μm and a 0.5-cm-diam image field. We use x-ray reflecting masks (patterned x-ray multilayer mirrors) which are fabricated on thick substrates and can be made relatively distortion free. Our design uses a laser produced plasma for the x-ray source. Better resolution and/or larger areas are possible with improvements in optic figures and source characteristics.

I. INTRODUCTION

New advances in the field of x-ray optics have been responsible for many new x-ray optical components such as normal incidence soft x-ray mirrors, beamsplitters, and highly dispersive multilayer mirrors.[1,2] These new optical components have made it possible to design and build new instruments such as x-ray microscopes, telescopes, waveguides, and interferometers. Another application is a new form of lithography which projects an image using soft x-ray radiation.

ondary photoelectrons generated in the photoresist (which could degrade the resolution) is small (~5 nm). At 4.5 nm, the x-ray absorption depth in resist is large (> 1 μm), and the depth of focus of our inverse Cassegrainian system is ±5.6 μm. This large depth of focus at the image plane along with the large x-ray absorption depth in resists at 4.5 nm would allow us to expose thick (~1 μm) resists. However, it should be noted that other soft-x-ray wavelengths (λ = 2–25 nm) can be used.

Reproduced fromJVST B 6, 2162, 1988, with permission from American Vacuum Society; Presented at 1988 EIPB conference, Ft. Lauderdale, FL

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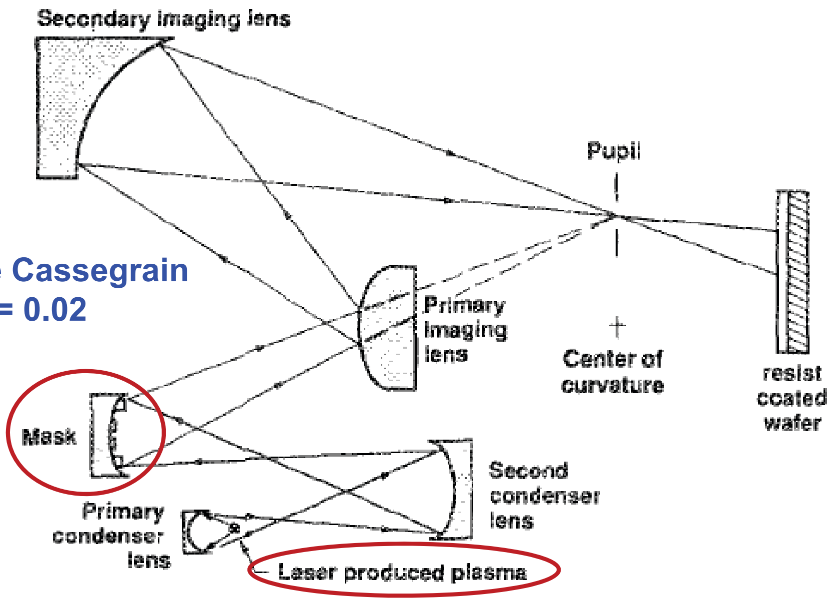
Both LPP source and ML masks were proposed in the Hawryluk & Seppala paper

5X, inverse Cassegrain
NA = 0.02



Reproduced from Hawryluk et al., JVST B 6, 2162, Nov/Dec 1988, with the permission of American Vacuum Society.

One year later, reflective EUV masks were fabricated

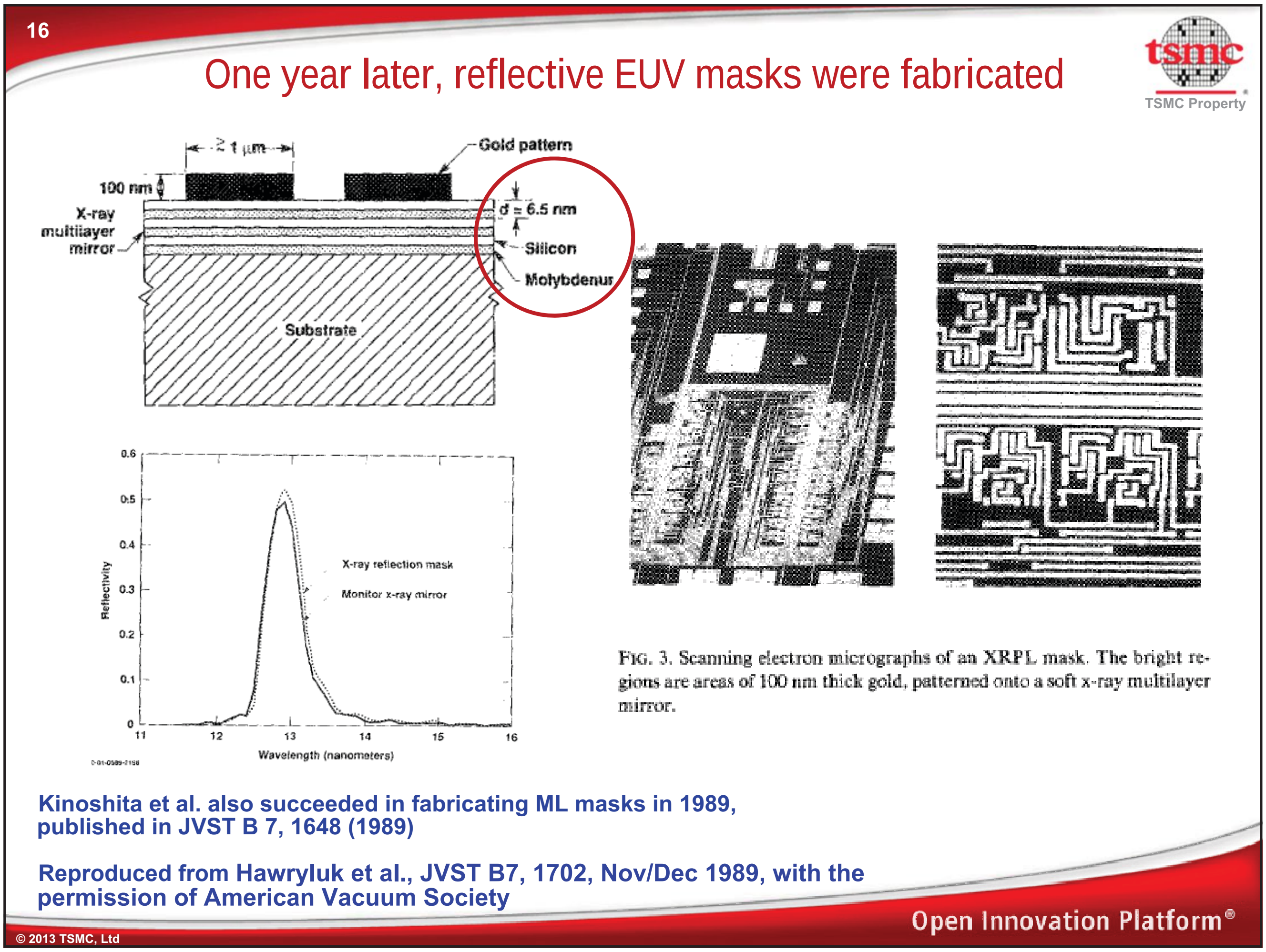


FIG. 3. Scanning electron micrographs of an XRPL mask. The bright regions are areas of 100 nm thick gold, patterned onto a soft x-ray multilayer mirror.

Kinoshita et al. also succeeded in fabricating ML masks in 1989, published in JVST B 7, 1648 (1989)

Reproduced from Hawryluk et al., JVST B7, 1702, Nov/Dec 1989, with the permission of American Vacuum Society

Encouraging exposure tool maker to develop EUVL for HVM

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Hawryluk, Yoshida, and Ceglio in Japan, Fall 1991

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LLNL signs CRADA with 3 US companies

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FRIDAY'S Newsline

Published twice weekly for employees of the University of California Lawrence Livermore National Laboratory Friday, October 16, 1992 Vol.17 No. 76

Watkins signs LLNL's largest CRADA

By Steve Wampler

Secretary of Energy James Watkins joined representatives from the Laboratory and three California firms yesterday to announce a collaborative research pact that may lead to important advances in manufacturing microelectronic components.

Such advances would permit manufacturing computer chips that are 10 times faster and contain 1,000 times more memory than today's chips, reported Lab scientists.

The four-year Collaborative Research and Development Agreement (CRADA) between the Laboratory and the three electronics companies was signed at the National Technology Initiative conference at the Santa Clara Convention Center.

Valued at $25.2 million, the new CRADA is the largest signed by the Laboratory to work with U.S. businesses to develop new technologies.

This agreement is part of a broader national program in soft

Photo by Bryan Quintard

Energy Secretary James Watkins, center, congratulates Lab scientists Andy Hawryluk, right, and Nat Ceglio on research he described as "concrete evidence of the success of National Technology Initiative." Watkins said NTI is "helping U.S. companies leapfrog to next generation technology."

**$12.6M from DOE;
$12.4M from Intel,
Ultratech Steppers,
and JMAR Technology**

Images courtesy of Nat Ceglio

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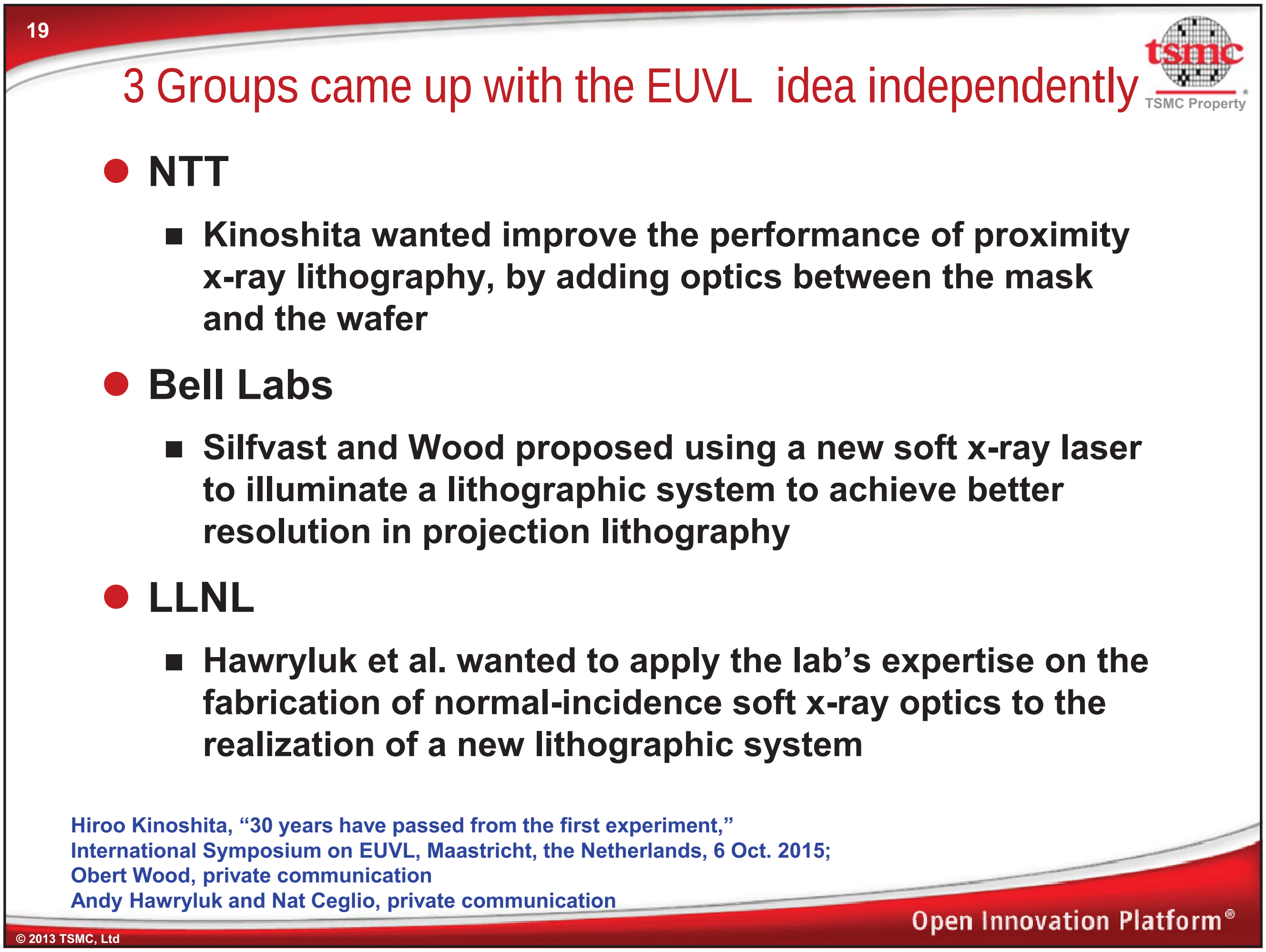
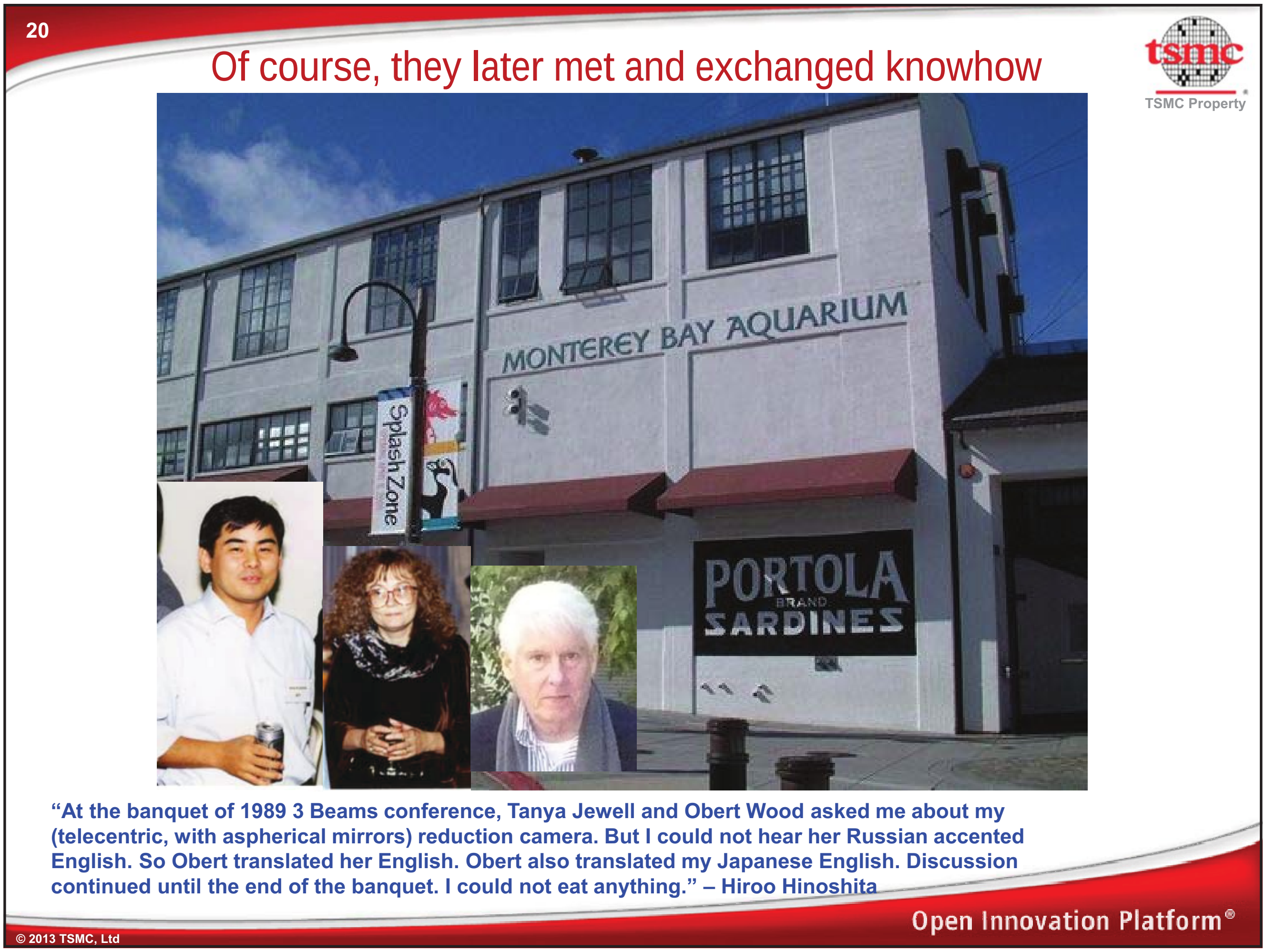


3 Groups came up with the EUVL idea independently

- NTT
  - Kinoshita wanted improve the performance of proximity x-ray lithography, by adding optics between the mask and the wafer
- Bell Labs
  - Silfvast and Wood proposed using a new soft x-ray laser to illuminate a lithographic system to achieve better resolution in projection lithography
- LLNL
  - Hawryluk et al. wanted to apply the lab’s expertise on the fabrication of normal-incidence soft x-ray optics to the realization of a new lithographic system

Hiroo Kinoshita, “30 years have passed from the first experiment,”
International Symposium on EUVL, Maastricht, the Netherlands, 6 Oct. 2015;
Obert Wood, private communication
Andy Hawryluk and Nat Ceglio, private communication



Of course, they later met and exchanged knowhow

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"At the banquet of 1989 3 Beams conference, Tanya Jewell and Obert Wood asked me about my (telecentric, with aspherical mirrors) reduction camera. But I could not hear her Russian accented English. So Obert translated her English. Obert also translated my Japanese English. Discussion continued until the end of the banquet. I could not eat anything." – Hiroo Hinoshita

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and…, From Russia with Litho

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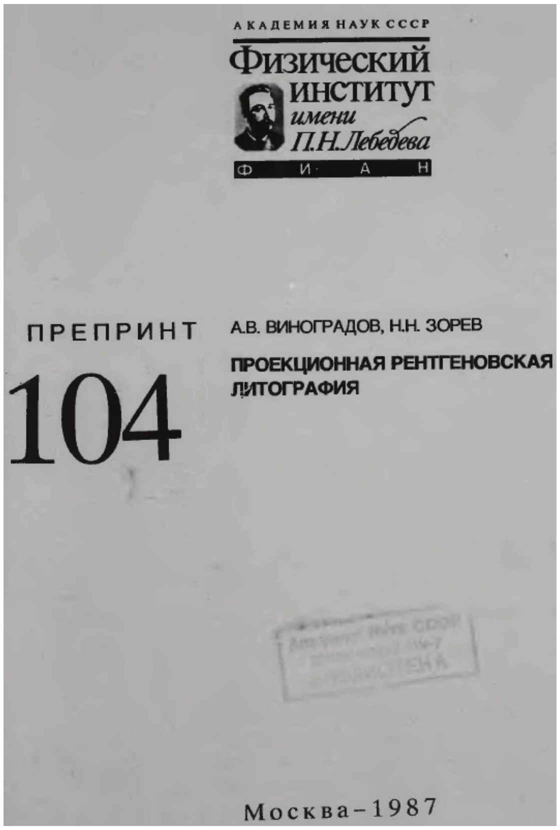


АКАДЕМИЯ НАУК СССР

Физический институт имени П.Н.Лебедева

ФИАН

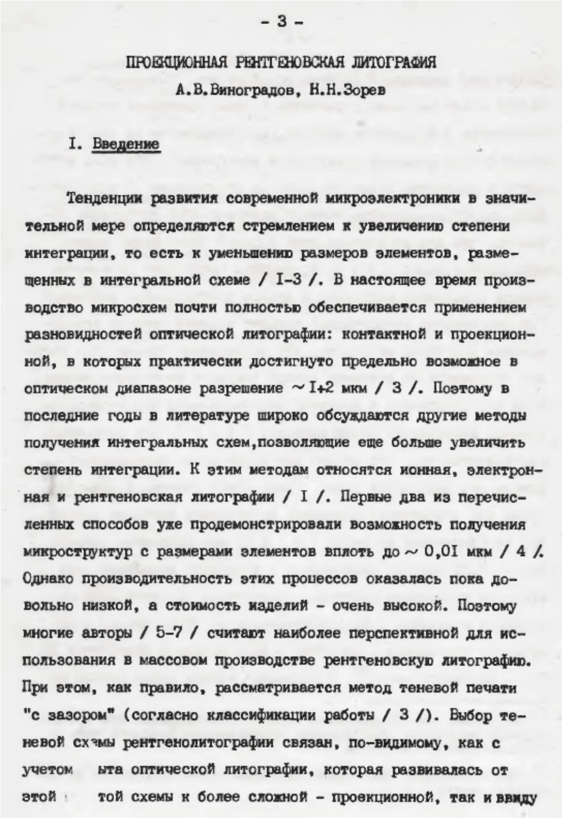
ПРЕПРИНТ

104

А.В. ВИНОГРАДОВ, Н.Н. ЗОРЕВ

ПРОЕКЦИОННАЯ РЕНТГЕНОВСКАЯ ЛИТОГРАФИЯ

Москва–1987



- 3 -

ПРОЕКЦИОННАЯ РЕНТГЕНОВСКАЯ ЛИТОГРАФИЯ

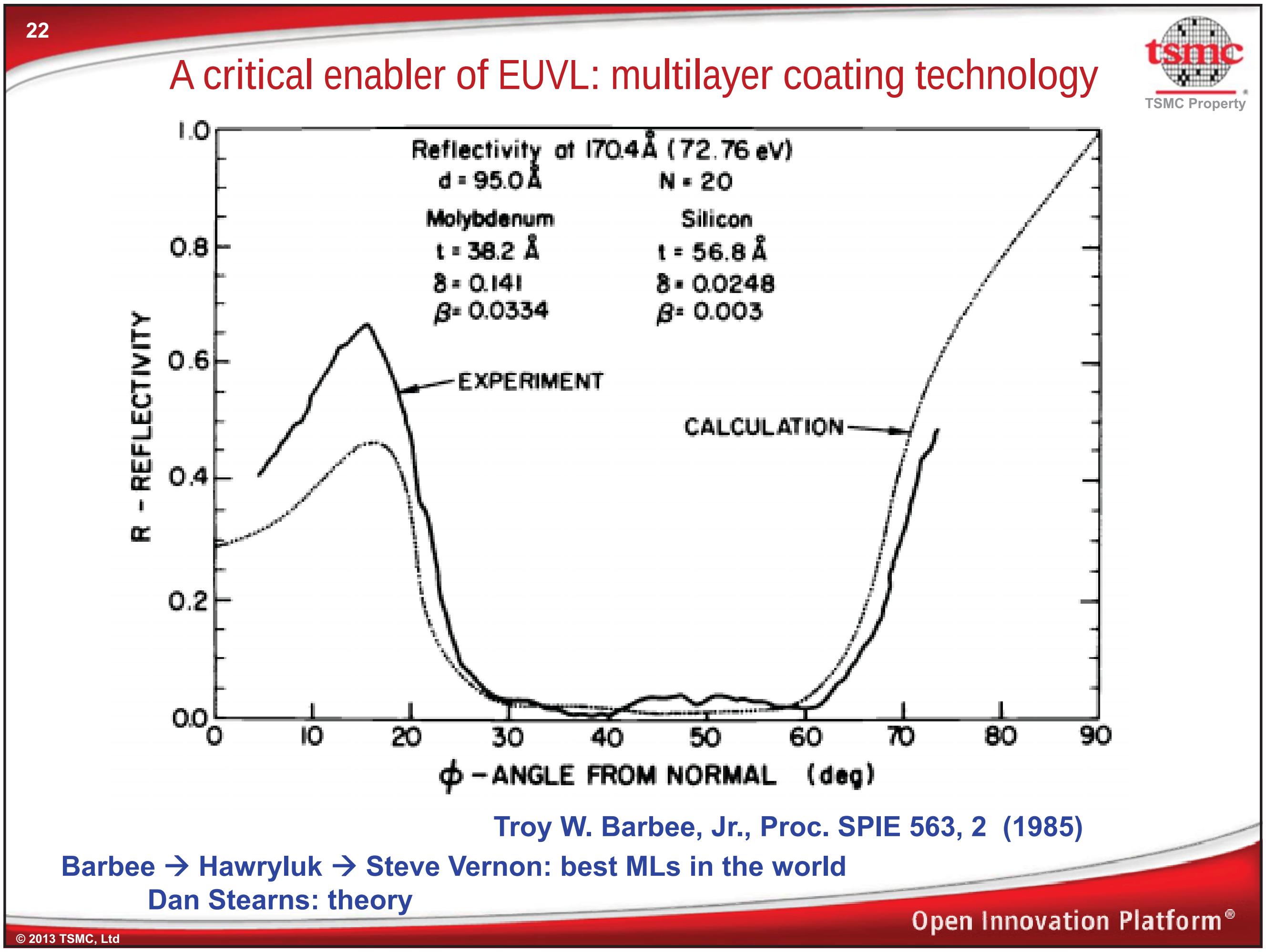
А.В.Виноградов, Н.Н.Зорев

I. Введение

Тенденции развития современной микроэлектроники в значительной мере определяются стремлением к увеличению степени интеграции, то есть к уменьшению размеров элементов, размещенных в интегральной схеме / I-3 /. В настоящее время производство микросхем почти полностью обеспечивается применением разновидностей оптической литографии: контактной и проекционной, в которых практически достигнуто предельно возможное в оптическом диапазоне разрешение ~ I+2 мкм / 3 /. Поэтому в последние годы в литературе широко обсуждаются другие методы получения интегральных схем,позволяющие еще больше увеличить степень интеграции. К этим методам относятся ионная, электронная и рентгеновская литографии / I /. Первые два из перечисленных способов уже продемонстрировали возможность получения микроструктур с размерами элементов вплоть до ~ 0,0I мкм / 4 /. Однако производительность этих процессов оказалась пока довольно низкой, а стоимость изделий – очень высокой. Поэтому многие авторы / 5-7 / считают наиболее перспективной для использования в массовом производстве рентгеновскую литографию. При этом, как правило, рассматривается метод теневой печати "с зазором" (согласно классификации работы / 3 /). Выбор теневой схемы рентгенолитографии связан, по-видимому, как с учетом ыта оптической литографии, которая развивалась от этой той схемы к более сложной – проекционной, так и ввиду

Material courtesy of Stefan Wurm

Open Innovation Platform®



A critical enabler of EUVL: multilayer coating technology

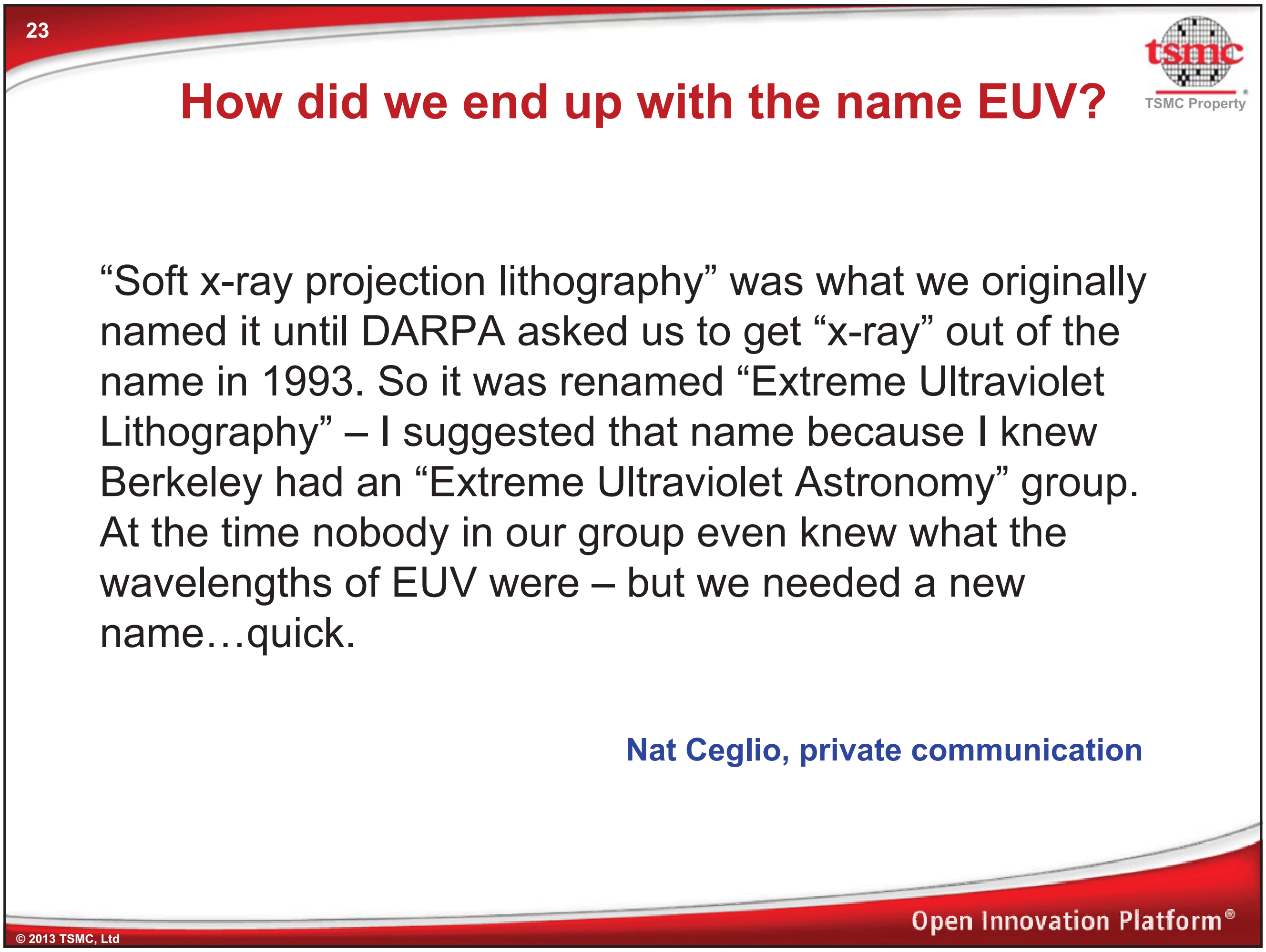
TSMC Property

Troy W. Barbee, Jr., Proc. SPIE 563, 2 (1985)

Barbee → Hawryluk → Steve Vernon: best MLs in the world

Dan Stearns: theory

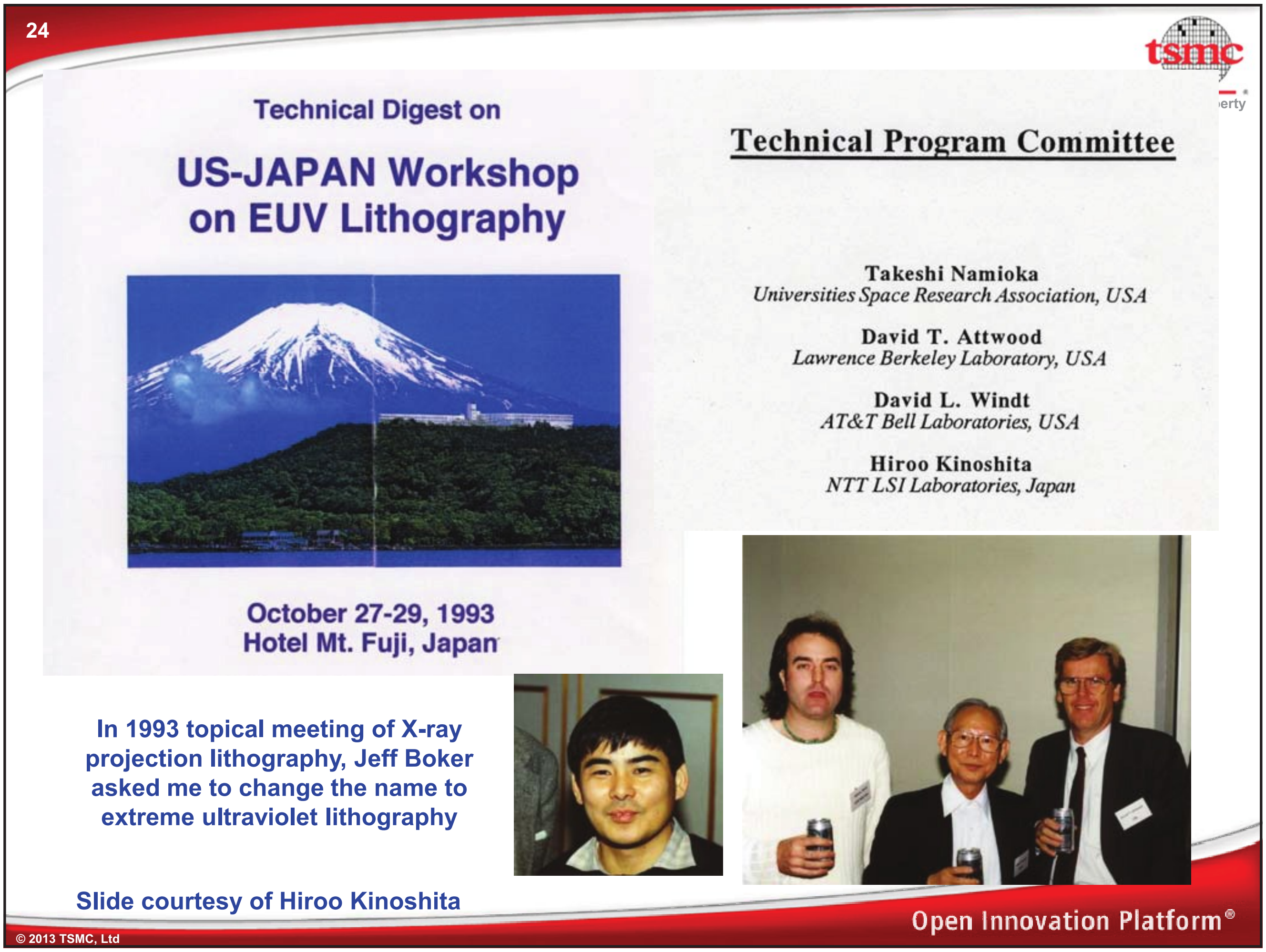
Open Innovation Platform®



How did we end up with the name EUV?

“Soft x-ray projection lithography” was what we originally named it until DARPA asked us to get “x-ray” out of the name in 1993. So it was renamed “Extreme Ultraviolet Lithography” – I suggested that name because I knew Berkeley had an “Extreme Ultraviolet Astronomy” group. At the time nobody in our group even knew what the wavelengths of EUV were – but we needed a new name…quick.

Nat Ceglio, private communication



Technical Digest on

US-JAPAN Workshop on EUV Lithography

October 27-29, 1993
Hotel Mt. Fuji, Japan

Technical Program Committee

Takeshi Namioka
Universities Space Research Association, USA

David T. Attwood
Lawrence Berkeley Laboratory, USA

David L. Windt
AT&T Bell Laboratories, USA

Hiroo Kinoshita
NTT LSI Laboratories, Japan

In 1993 topical meeting of X-ray projection lithography, Jeff Boker asked me to change the name to extreme ultraviolet lithography

Slide courtesy of Hiroo Kinoshita

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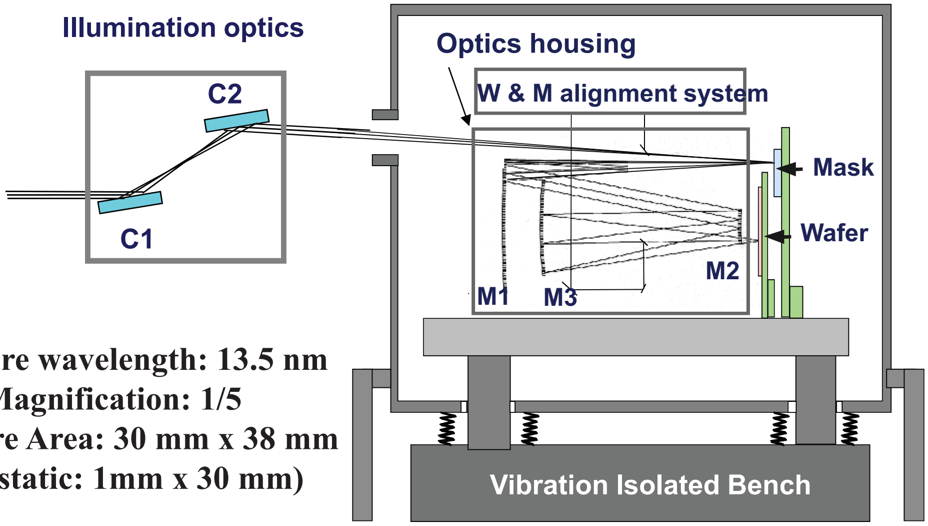
TSMC Property

Kinoshita moved to Himeji Institute of Technology in 1995

- **HIT, in collaboration with Hitachi and Nikon started to develop a three-aspheric mirror system called the ETS-1 in 1996. System was built in 1998**



Exposure wavelength: 13.5 nm
Magnification: 1/5
Exposure Area: 30 mm x 38 mm
(static: 1mm x 30 mm)

Slide courtesy of Hiroo Kinoshita

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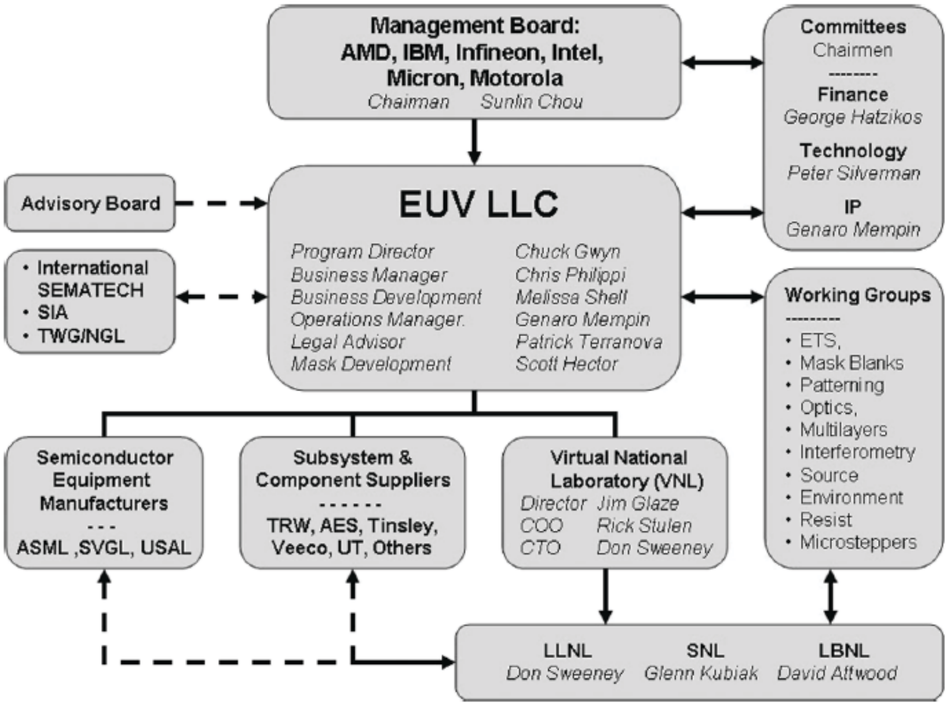
EUV LLC was established to continue to develop EUV



Management Board:
AMD, IBM, Infineon, Intel,
Micron, Motorola
Chairman *Sunlin Chou*

Committees
Chairmen

Finance
George Hatzikos
Technology
Peter Silverman
IP
Genaro Mempin

Advisory Board

- **International SEMATECH**
- **SIA**
- **TWG/NGL**

EUV LLC

Program Director	*Chuck Gwyn*
Business Manager	*Chris Philippi*
Business Development	*Melissa Shell*
Operations Manager.	*Genaro Mempin*
Legal Advisor	*Patrick Terranova*
Mask Development	*Scott Hector*

Working Groups

- ETS,
- Mask Blanks
- Patterning
- Optics,
- Multilayers
- Interferometry
- Source
- Environment
- Resist
- Microsteppers

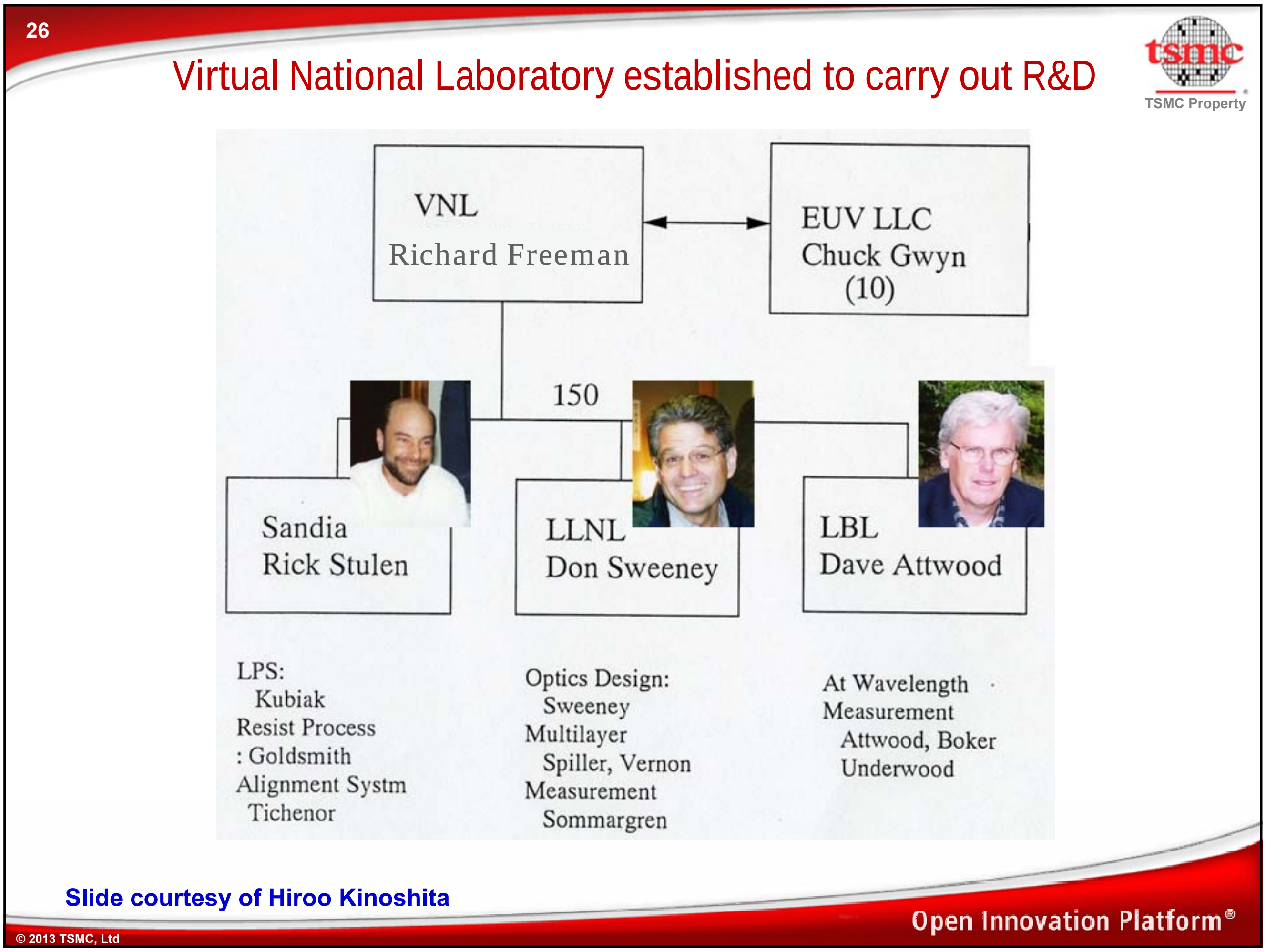
Semiconductor Equipment Manufacturers
- - -
ASML ,SVGL, USAL

Subsystem & Component Suppliers
- - - - - -
TRW, AES, Tinsley, Veeco, UT, Others

Virtual National Laboratory (VNL)
Director *Jim Glaze*
COO *Rick Stulen*
CTO *Don Sweeney*

LLNL	**SNL**	**LBNL**
Don Sweeney	*Glenn Kubiak*	*David Attwood*

from EUV LLC: An Historical Perspective, by Chuck Gwyn and Stefan Wurm
in EUV Lithography, edited by Vivek Bakshi, SPIE Press 2009



Virtual National Laboratory established to carry out R&D

TSMC Property

VNL
Richard Freeman

EUV LLC
Chuck Gwyn
(10)

150

Sandia
Rick Stulen

LLNL
Don Sweeney

LBL
Dave Attwood

LPS:
Kubiak
Resist Process
: Goldsmith
Alignment Systm
Tichenor

Optics Design:
Sweeney
Multilayer
Spiller, Vernon
Measurement
Sommargren

At Wavelength
Measurement
Attwood, Boker
Underwood

Slide courtesy of Hiroo Kinoshita

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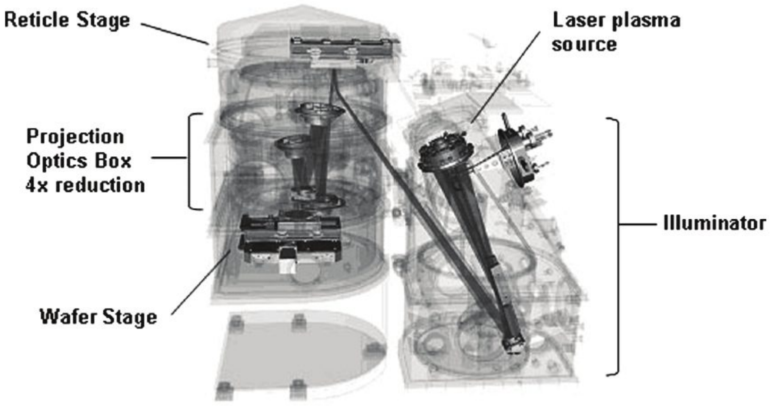
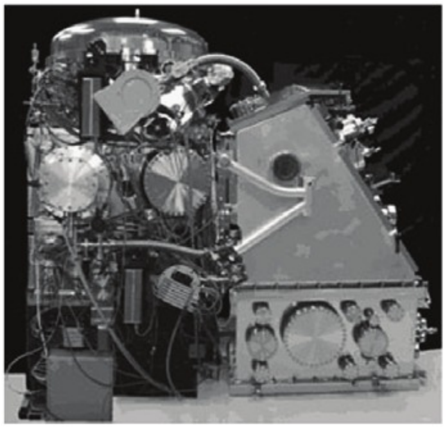
Culmination of EUV LLC work – ETS

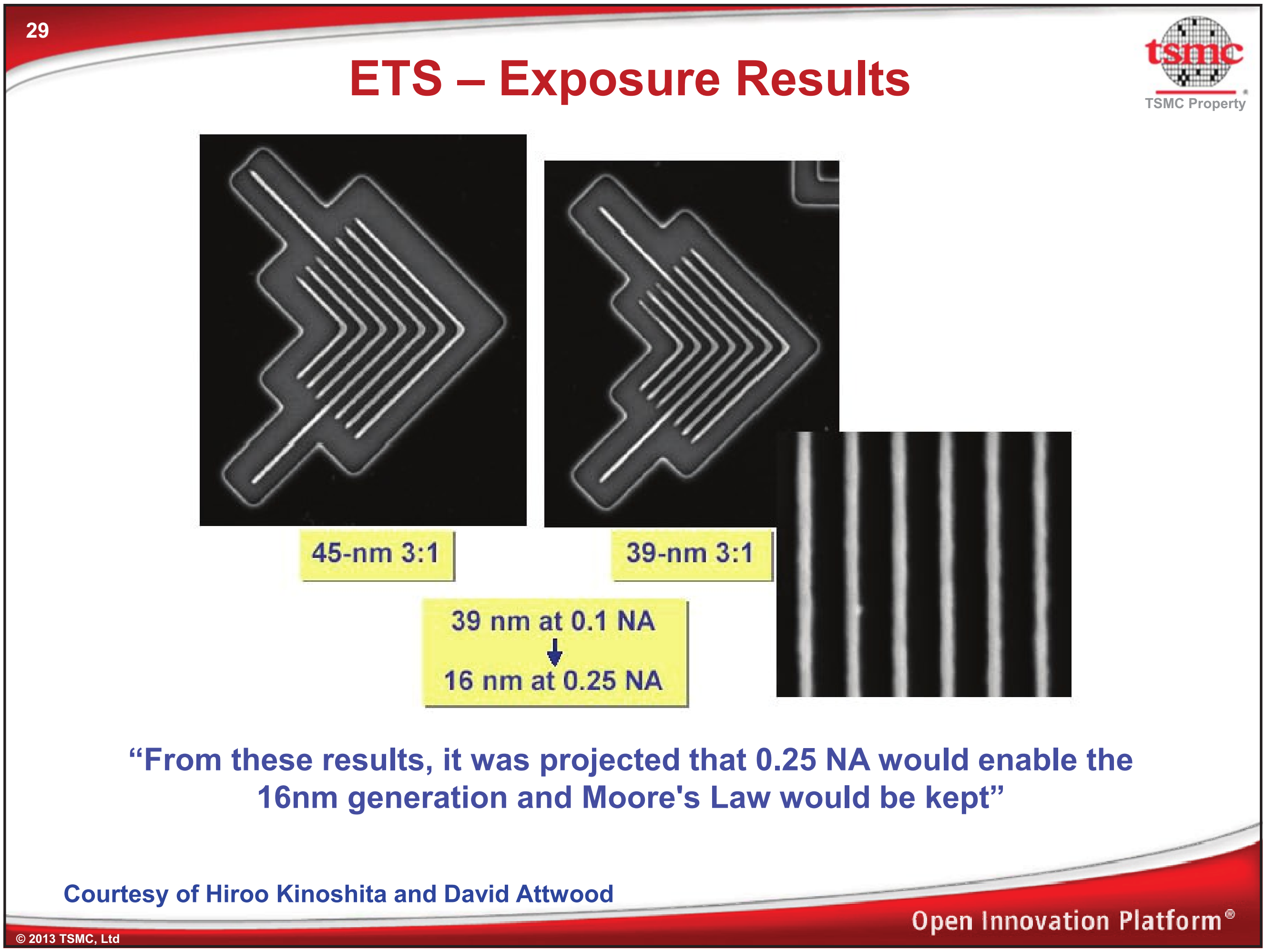
0.1 NA, 4 mirrors, 24x32.5 mm imaging field





Schematic drawing **Initial assembly**

from EUV LLC: An Historical Perspective, by Chuck Gwyn and Stefan Wurm in EUV Lithography, edited by Vivek Bakshi, SPIE Press 2009



29

TSMC Property

ETS – Exposure Results

45-nm 3:1

39-nm 3:1

39 nm at 0.1 NA
↓
16 nm at 0.25 NA

"From these results, it was projected that 0.25 NA would enable the 16nm generation and Moore's Law would be kept"

Courtesy of Hiroo Kinoshita and David Attwood

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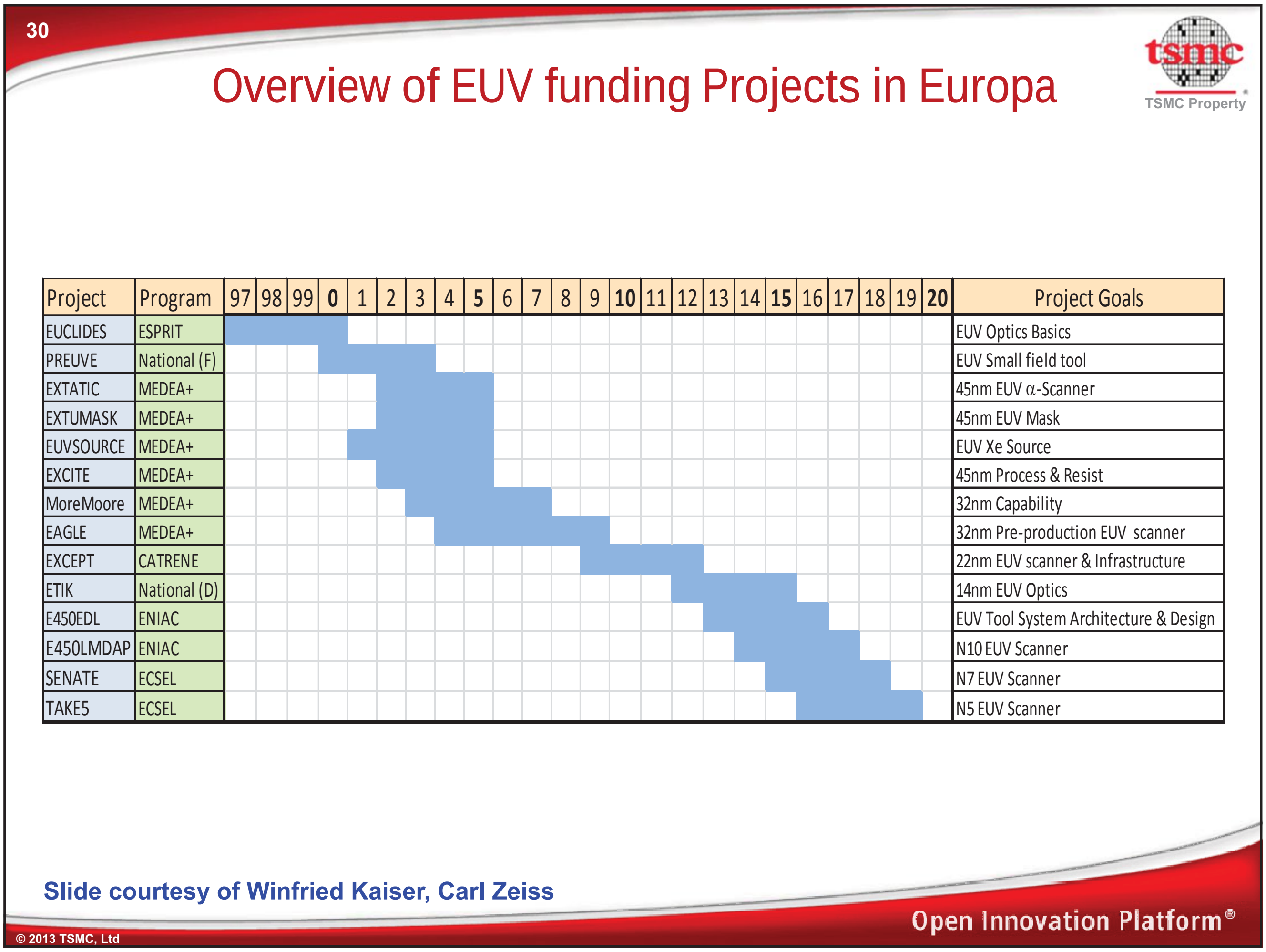

TSMC Property

Overview of EUV funding Projects in Europa

Project	Program	97	98	99	**0**	1	2	3	4	**5**	6	7	8	9	**10**	11	12	13	14	**15**	16	17	18	19	**20**	Project Goals
EUCLIDES	ESPRIT	🟦	🟦	🟦	🟦																					EUV Optics Basics
PREUVE	National (F)				🟦	🟦	🟦	🟦																		EUV Small field tool
EXTATIC	MEDEA+						🟦	🟦	🟦	🟦																45nm EUV α-Scanner
EXTUMASK	MEDEA+						🟦	🟦	🟦	🟦																45nm EUV Mask
EUVSOURCE	MEDEA+					🟦	🟦	🟦	🟦	🟦																EUV Xe Source
EXCITE	MEDEA+						🟦	🟦	🟦	🟦																45nm Process & Resist
MoreMoore	MEDEA+							🟦	🟦	🟦	🟦	🟦														32nm Capability
EAGLE	MEDEA+								🟦	🟦	🟦	🟦	🟦	🟦												32nm Pre-production EUV scanner
EXCEPT	CATRENE													🟦	🟦	🟦	🟦									22nm EUV scanner & Infrastructure
ETIK	National (D)																🟦	🟦	🟦	🟦						14nm EUV Optics
E450EDL	ENIAC																	🟦	🟦	🟦	🟦					EUV Tool System Architecture & Design
E450LMDAP	ENIAC																		🟦	🟦	🟦	🟦				N10 EUV Scanner
SENATE	ECSEL																			🟦	🟦	🟦	🟦			N7 EUV Scanner
TAKE5	ECSEL																				🟦	🟦	🟦	🟦		N5 EUV Scanner

Slide courtesy of Winfried Kaiser, Carl Zeiss

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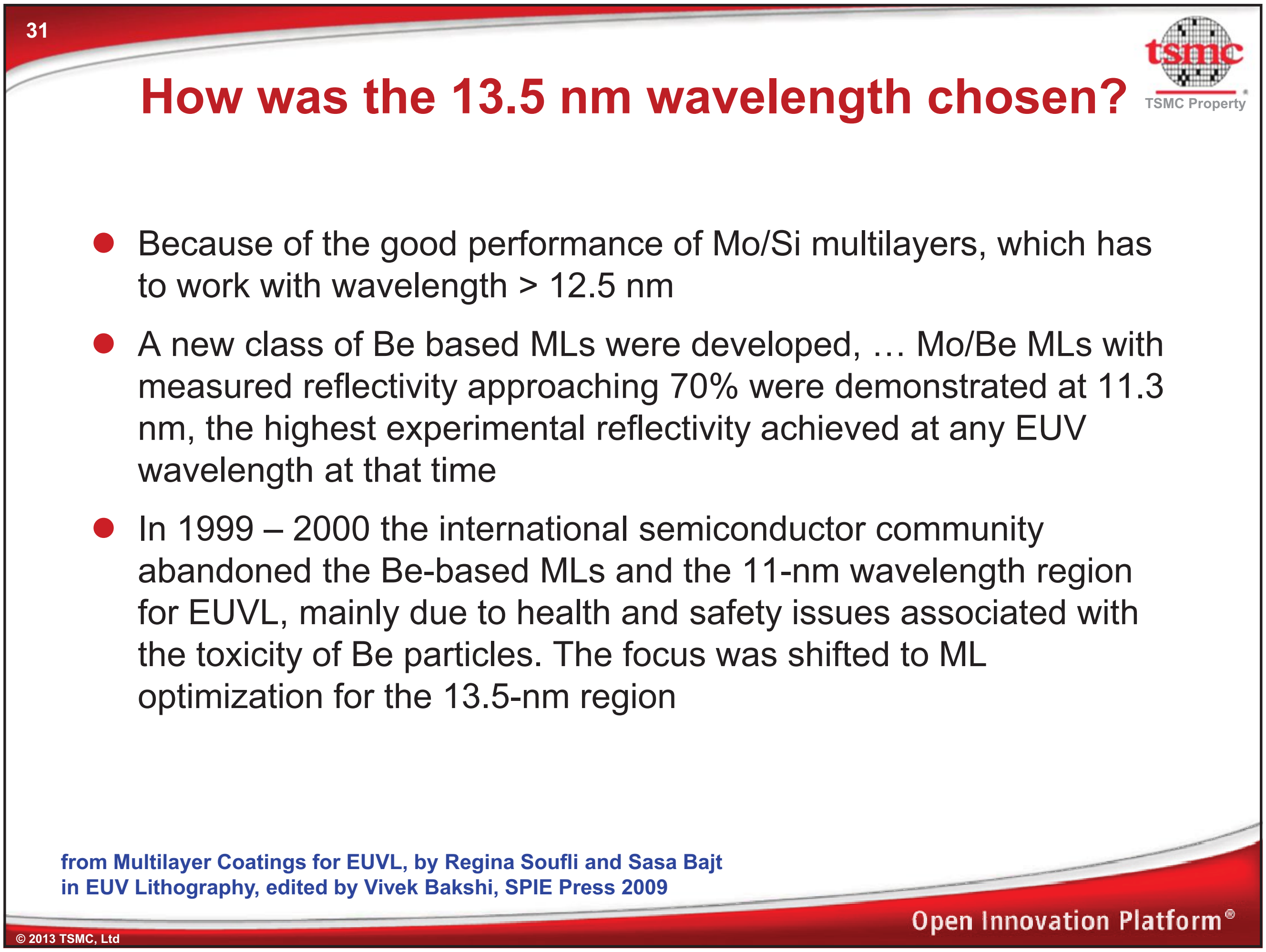
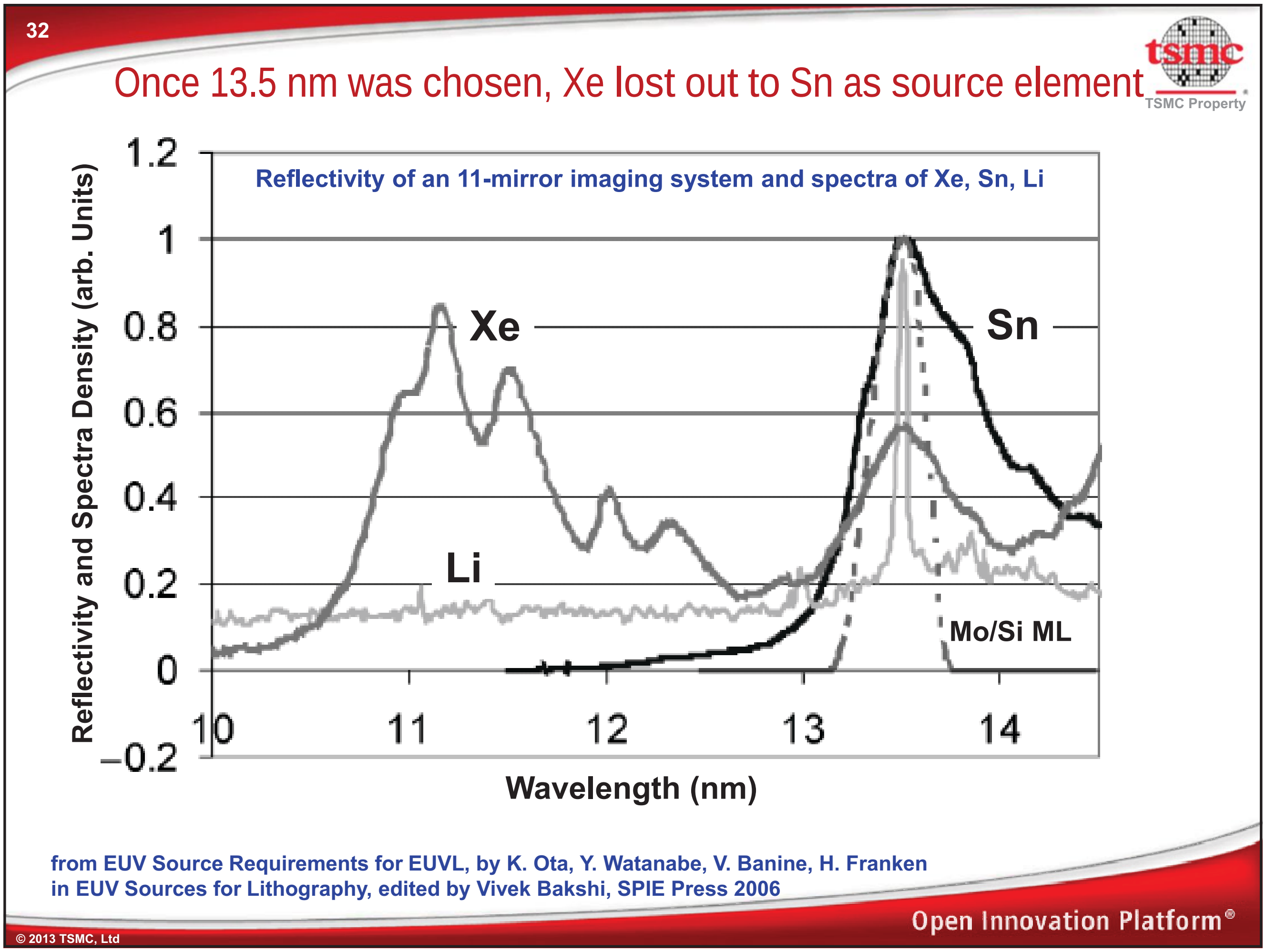


How was the 13.5 nm wavelength chosen?

- Because of the good performance of Mo/Si multilayers, which has to work with wavelength > 12.5 nm
- A new class of Be based MLs were developed, … Mo/Be MLs with measured reflectivity approaching 70% were demonstrated at 11.3 nm, the highest experimental reflectivity achieved at any EUV wavelength at that time
- In 1999 – 2000 the international semiconductor community abandoned the Be-based MLs and the 11-nm wavelength region for EUVL, mainly due to health and safety issues associated with the toxicity of Be particles. The focus was shifted to ML optimization for the 13.5-nm region

from Multilayer Coatings for EUVL, by Regina Soufli and Sasa Bajt
in EUV Lithography, edited by Vivek Bakshi, SPIE Press 2009



32

Once 13.5 nm was chosen, Xe lost out to Sn as source element

TSMC Property

from EUV Source Requirements for EUVL, by K. Ota, Y. Watanabe, V. Banine, H. Franken
in EUV Sources for Lithography, edited by Vivek Bakshi, SPIE Press 2006

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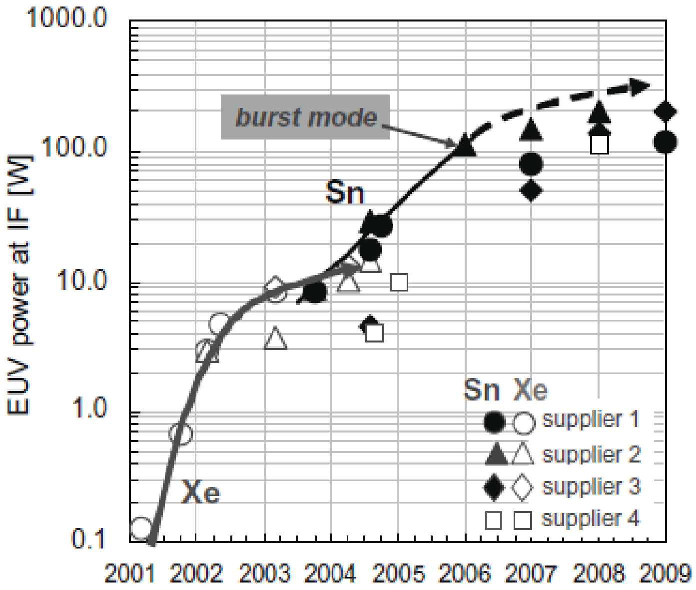
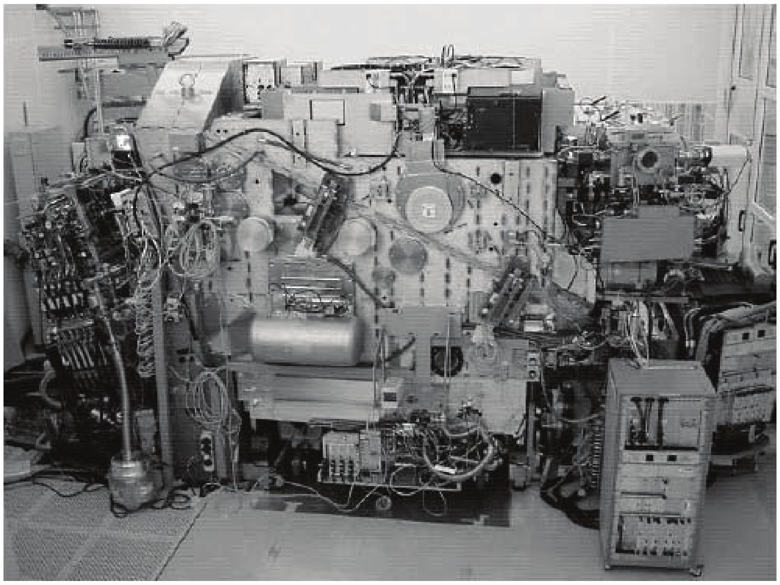
By early 2006, Sn had already been selected by ASML



Since available power will determine the litho tool throughput, and Sn fueled sources are the most promising in terms of high power, ASML decided to incorporate a Sn discharge source on the AD-tool (see picture in Figure 5). Sn sources can provide the necessary photons for throughput, but they also generate debris which needs to be mitigated.

Hans Meiling et al., "First performance results of the ASML alpha demo tool," Proc. SPIE 6151, 615108 (2006)

SPIE AL 2006: ASML ADT in image qualification



	AD-tool
λ	13.5 nm
NA range	0.15 – 0.25
Field size	26 x 33 mm^2
Wafer size	300 mm
Magnification	4x
Flare	16%
Dense L/S	40 nm
Isolated lines	30 nm
Iso/dense contact	55 nm
Overlay	12 nm
Throughput	~10 wph

Hans Meiling et al., "First performance results of the ASML alpha demo tool," Proc. SPIE 6151, 615108 (2006)

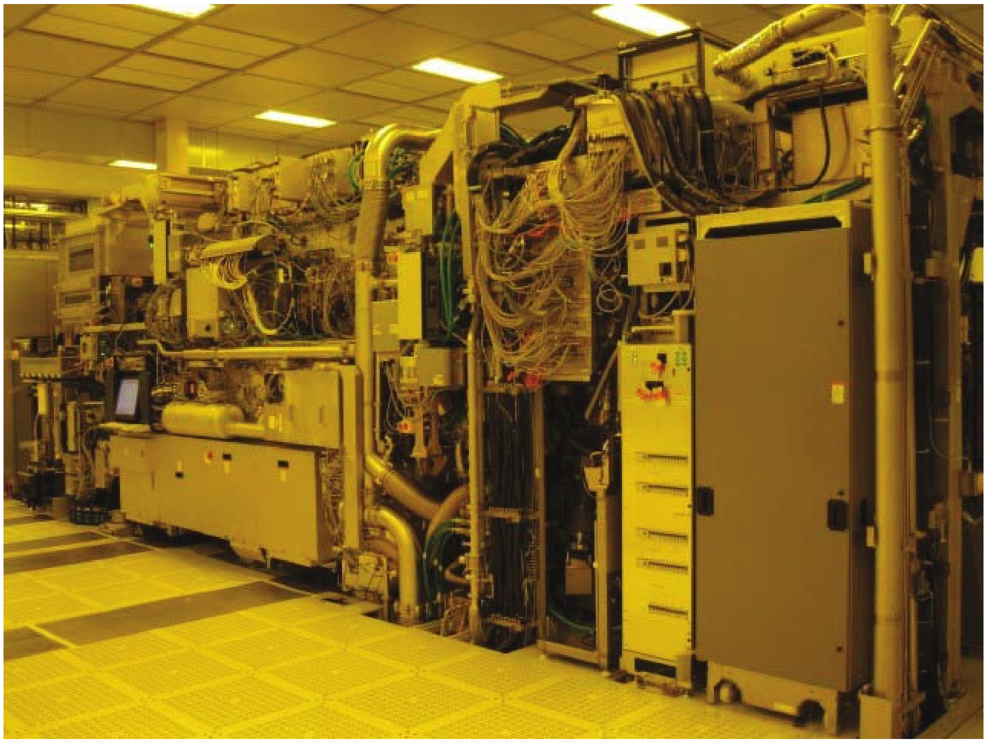
Summer 2011: NXE3100 Arrives in Taiwan

TSMC Property

One of several scanner shipments arriving in Taiwan

NXE3100: Installation Nearly Complete

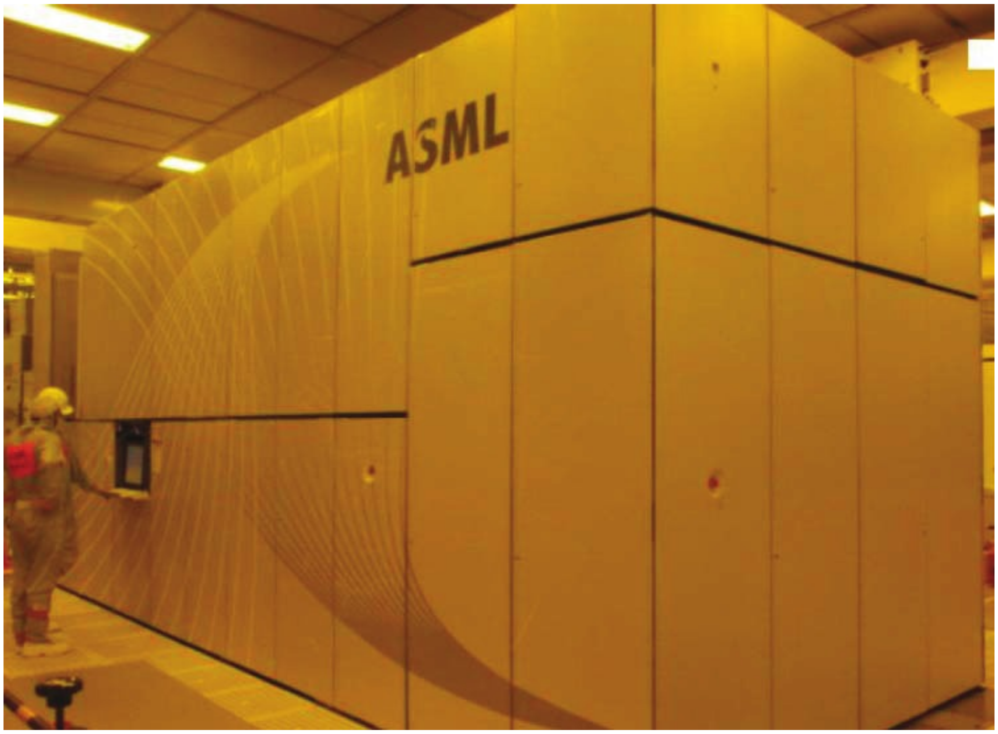
TSMC Property



TSMC, October 2011

TSMC Property

NXE3300: Installation Complete



TSMC, October 2013

TSMC Property

Mid-module of NXE3350 Arriving at TSMC

2016

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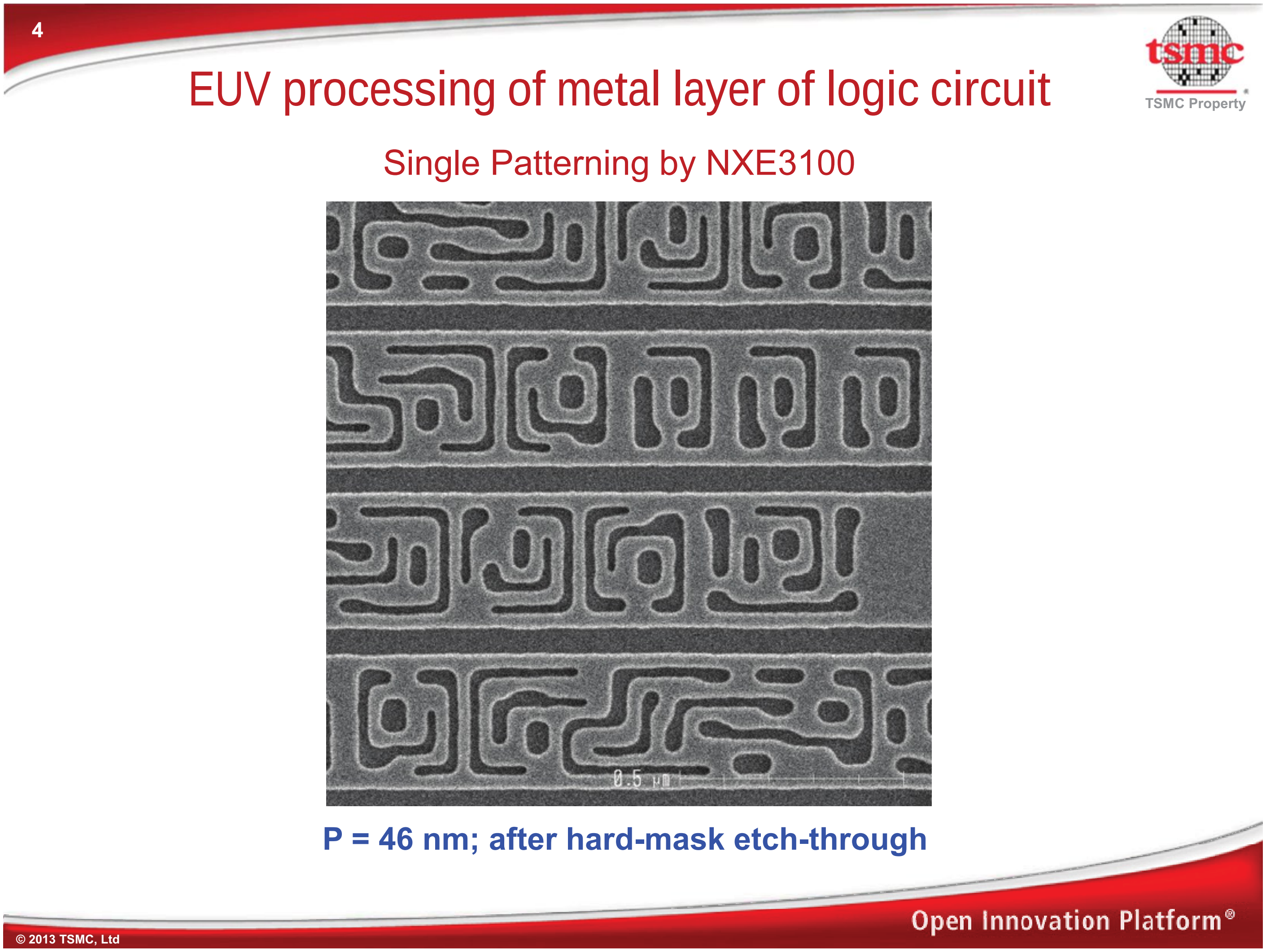

TSMC Property

EUV processing of metal layer of logic circuit

Single Patterning by NXE3100

P = 46 nm; after hard-mask etch-through

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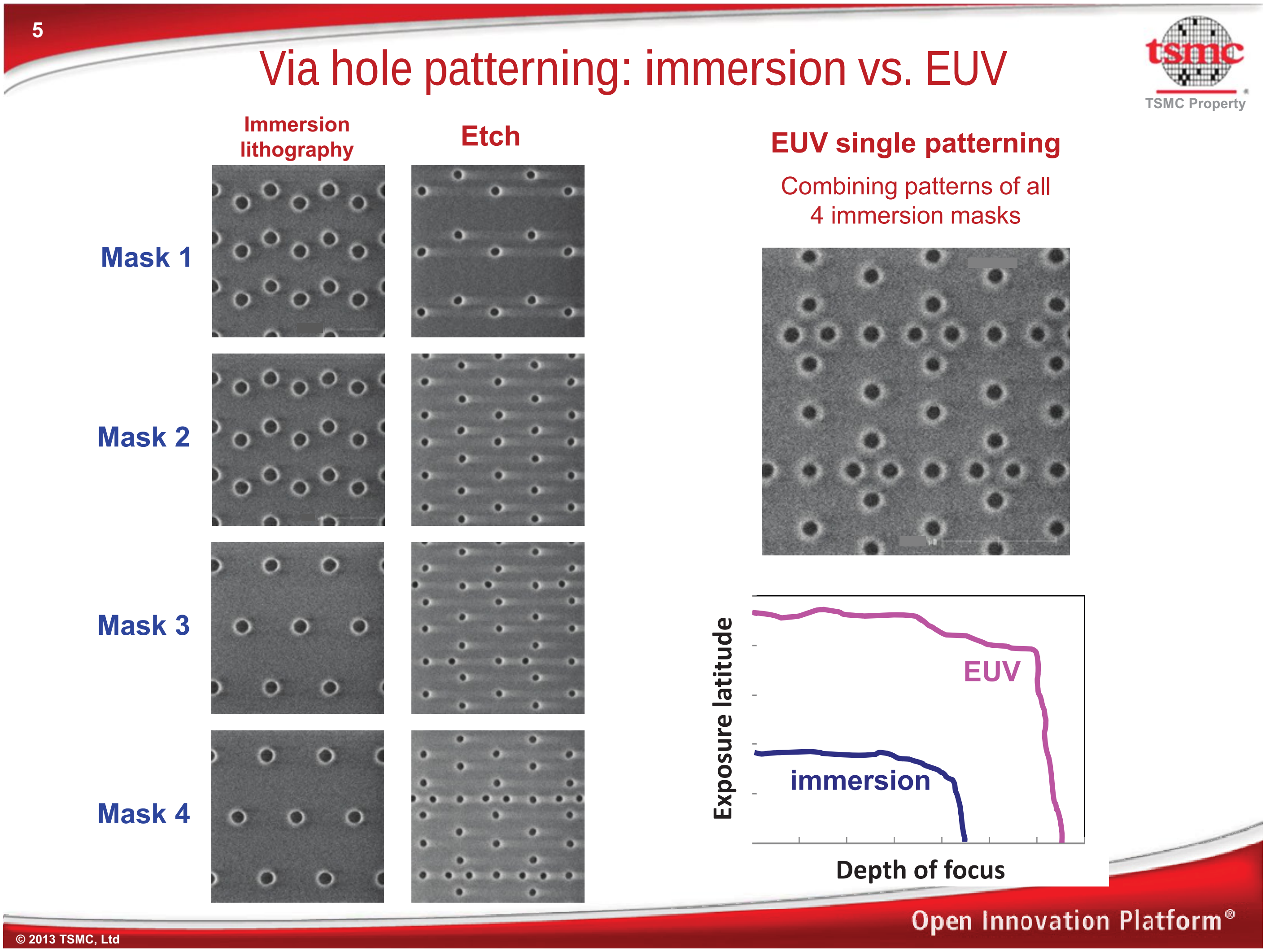

5

Via hole patterning: immersion vs. EUV

TSMC Property

Immersion lithography

Etch

Mask 1

Mask 2

Mask 3

Mask 4

EUV single patterning

Combining patterns of all
4 immersion masks

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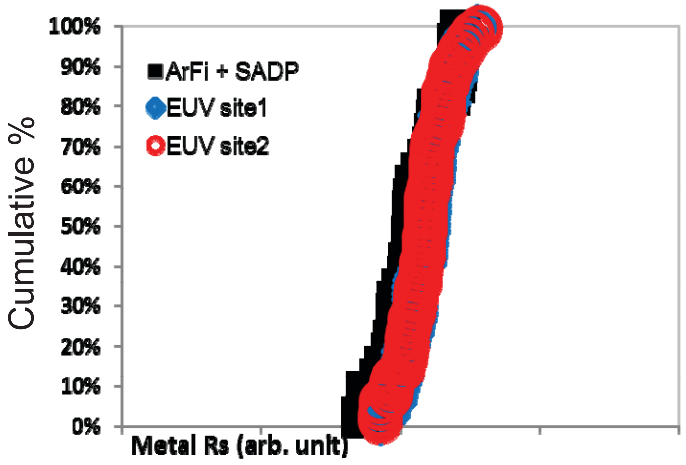
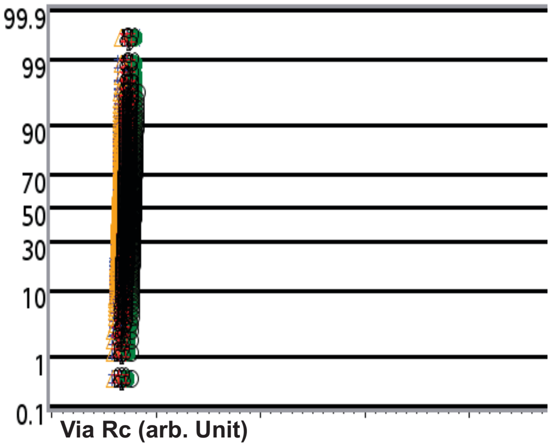
Same electrical performance as multiple patterning

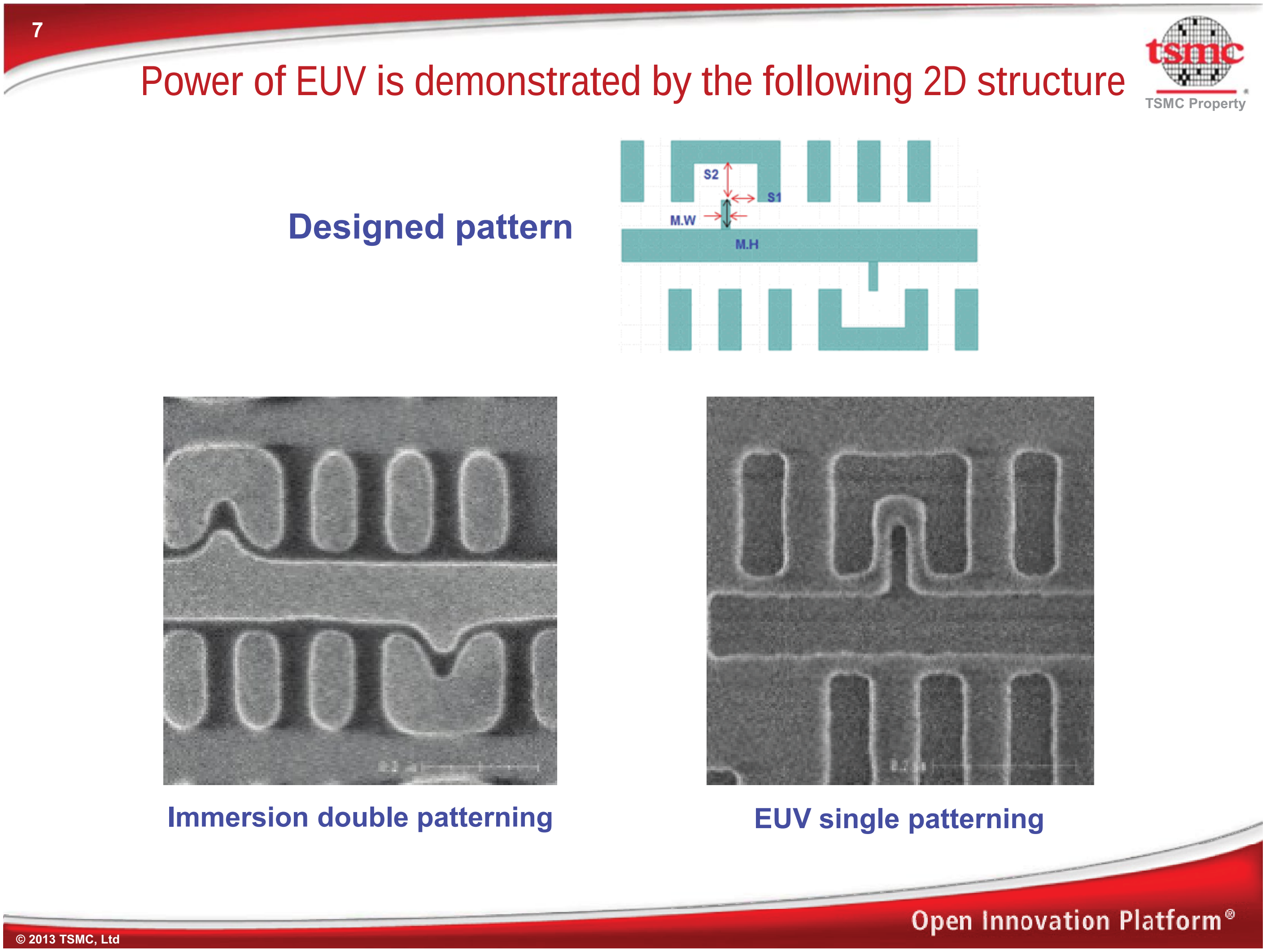
TSMC Property


Metal1 Rs WAT


Via Rc WAT

- **Based on the same layout, CD target, and film stack, EUVL has achieved comparable electrical performance as the ArF immersion baseline**

Today, 2:10 pm (9782-2): EUV for sub-10nm logic technology



7

Power of EUV is demonstrated by the following 2D structure

TSMC Property

Designed pattern

Immersion double patterning

EUV single patterning

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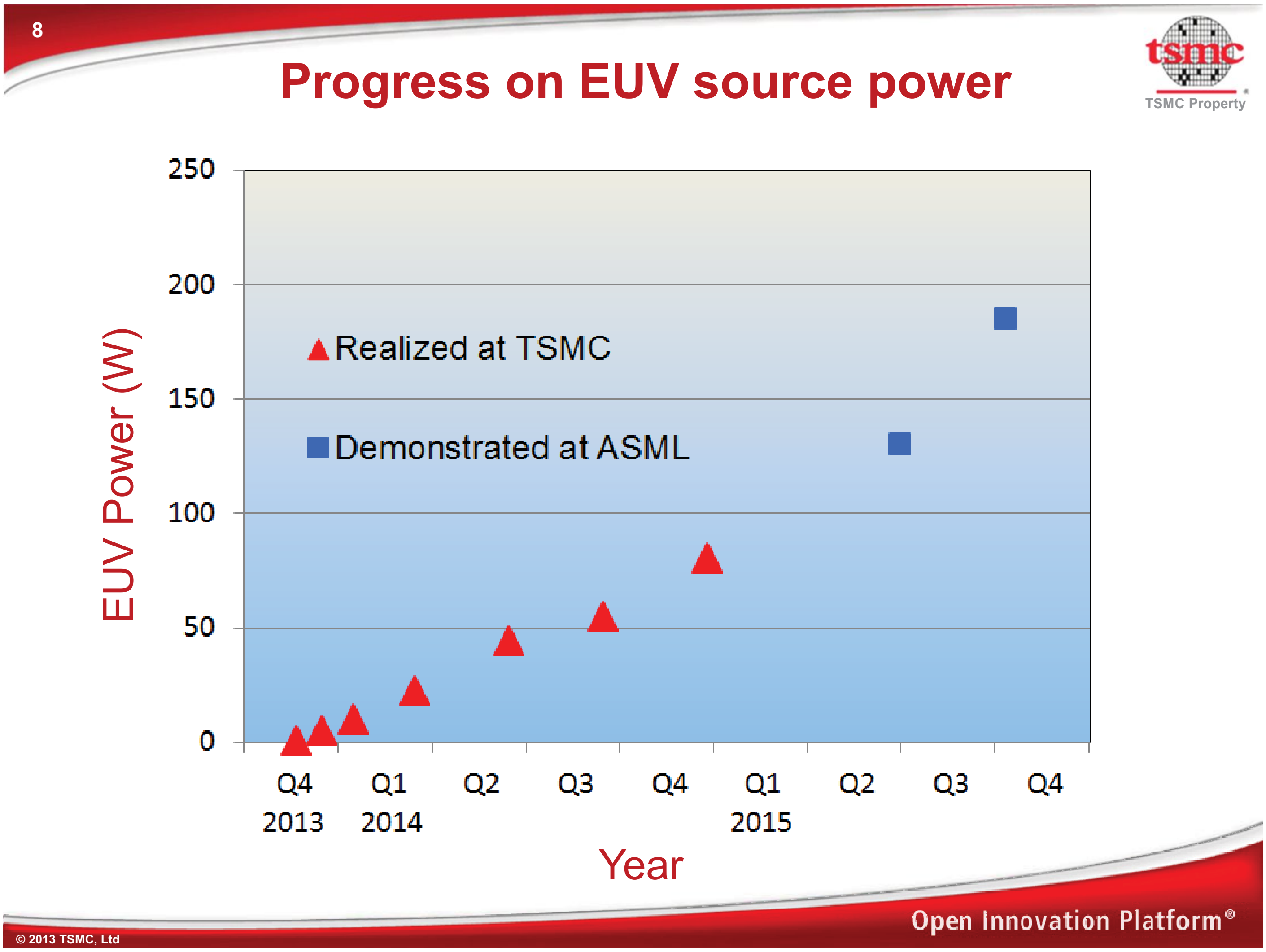

8

Progress on EUV source power

TSMC Property

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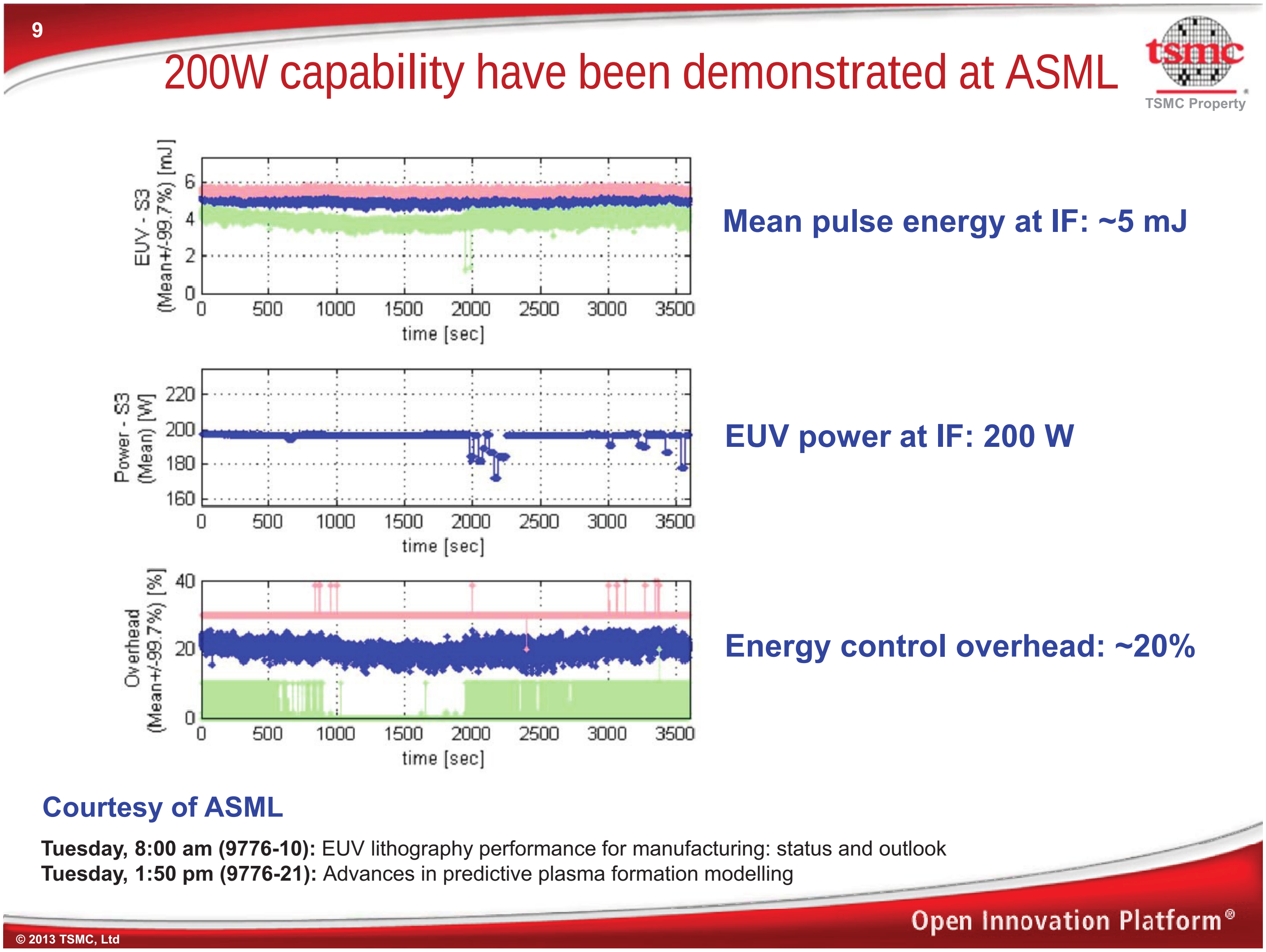

200W capability have been demonstrated at ASML

TSMC Property

Mean pulse energy at IF: ~5 mJ

EUV power at IF: 200 W

Energy control overhead: ~20%

Courtesy of ASML

Tuesday, 8:00 am (9776-10): EUV lithography performance for manufacturing: status and outlook
Tuesday, 1:50 pm (9776-21): Advances in predictive plasma formation modelling

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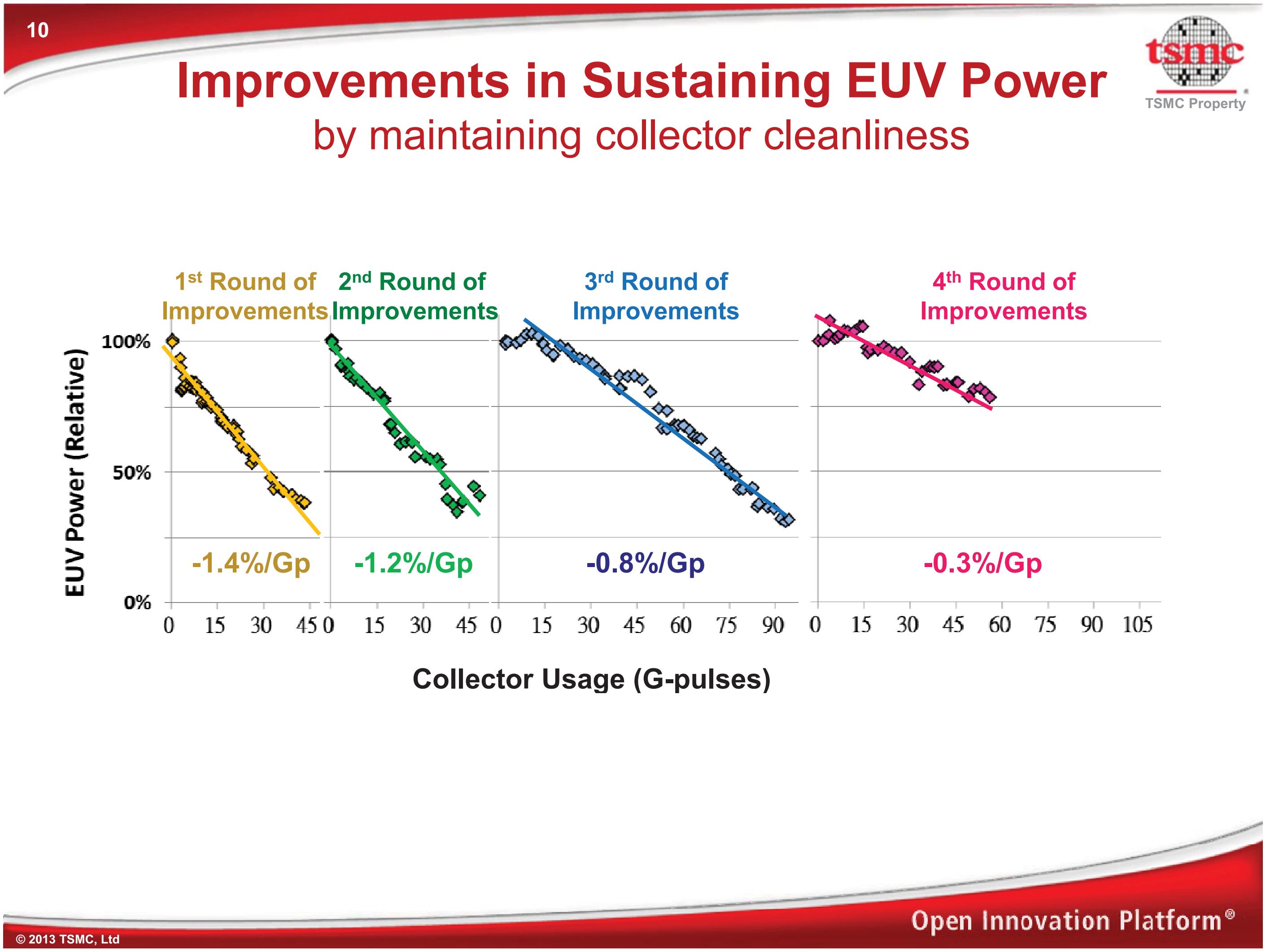

10

Improvements in Sustaining EUV Power

by maintaining collector cleanliness

TSMC Property

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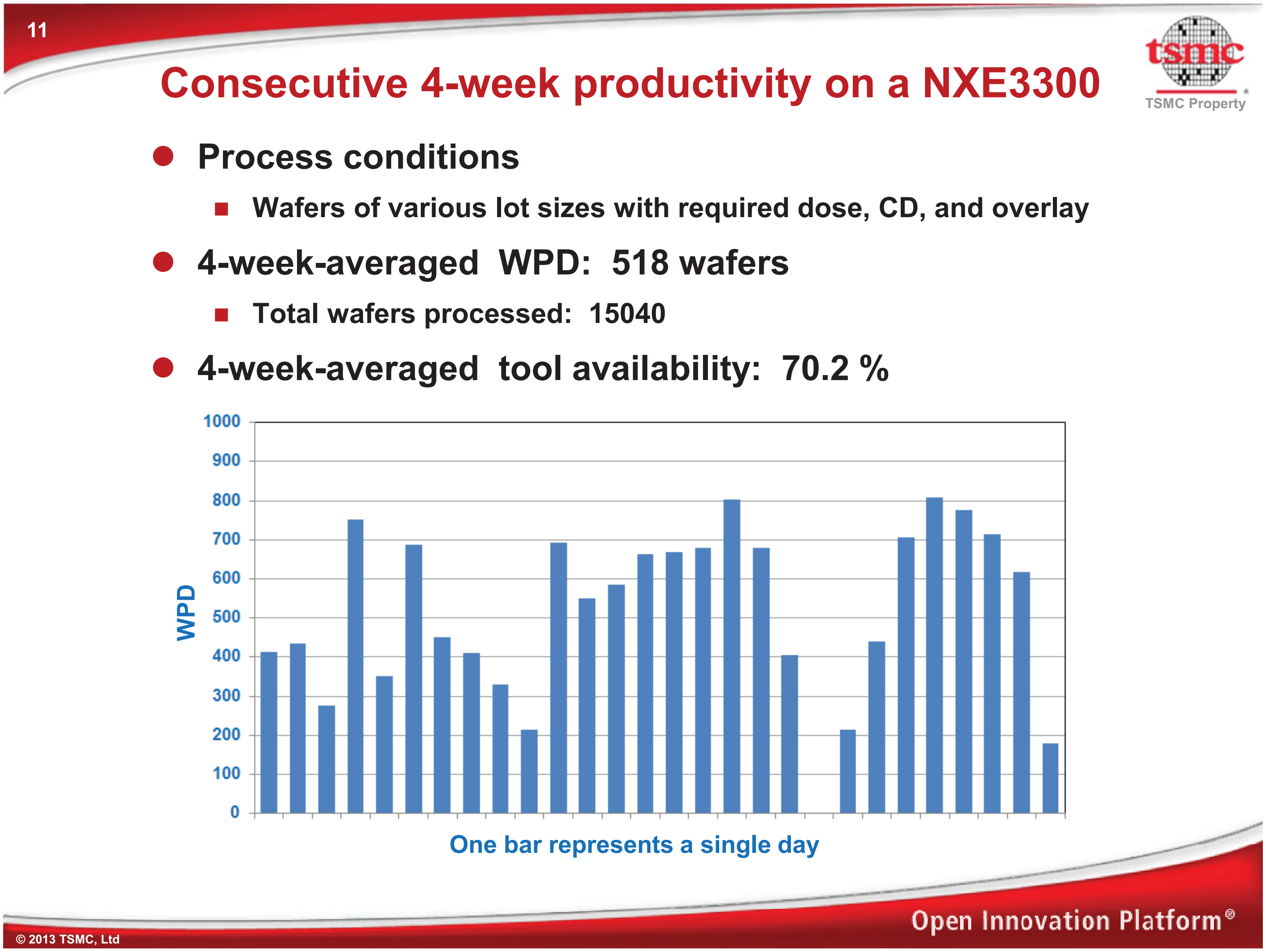
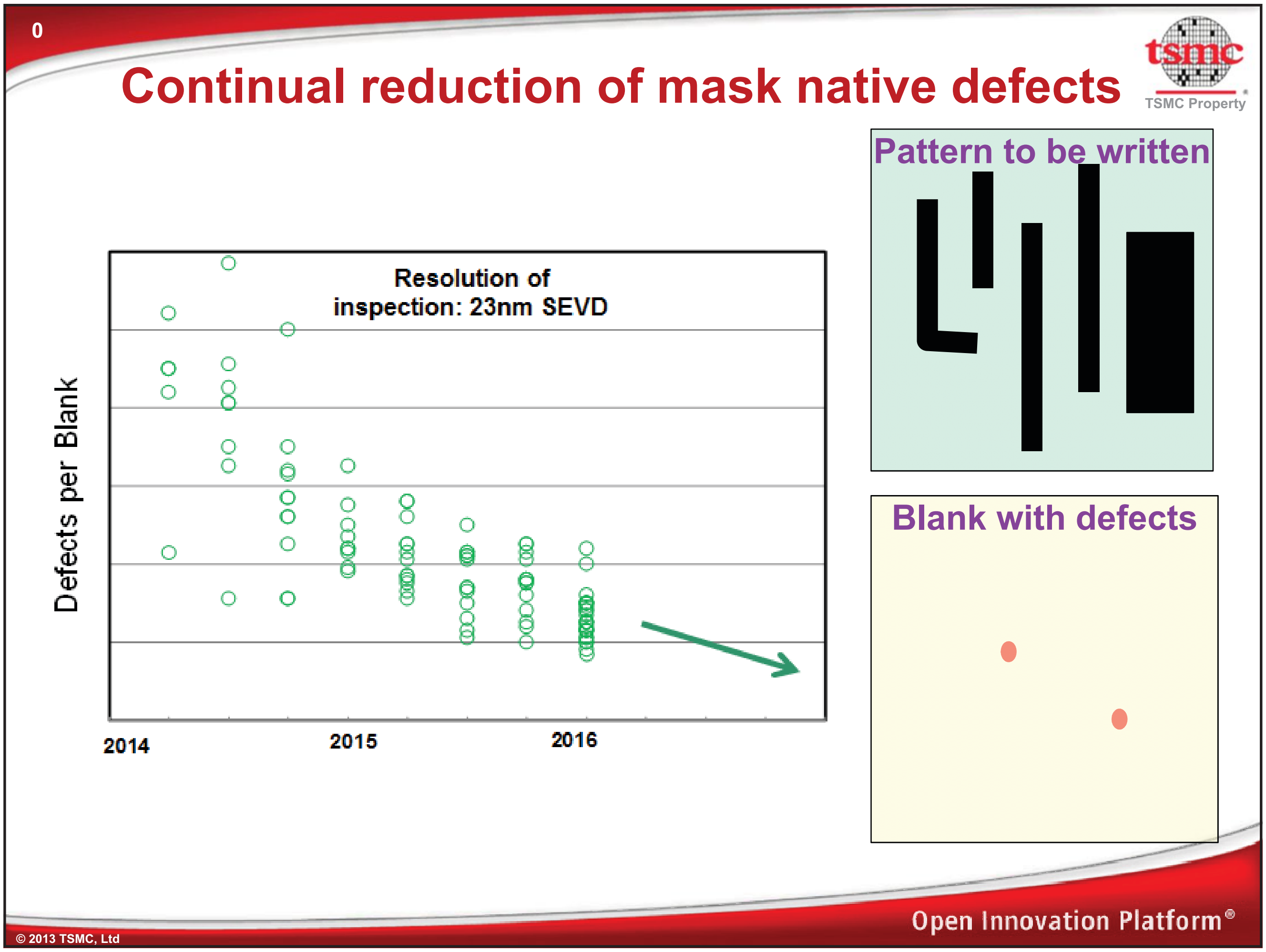


Consecutive 4-week productivity on a NXE3300

- **Process conditions**
  - Wafers of various lot sizes with required dose, CD, and overlay
- **4-week-averaged WPD: 518 wafers**
  - Total wafers processed: 15040
- **4-week-averaged tool availability: 70.2 %**

One bar represents a single day



Continual reduction of mask native defects

TSMC Property

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1

Can we keep the mask clean?

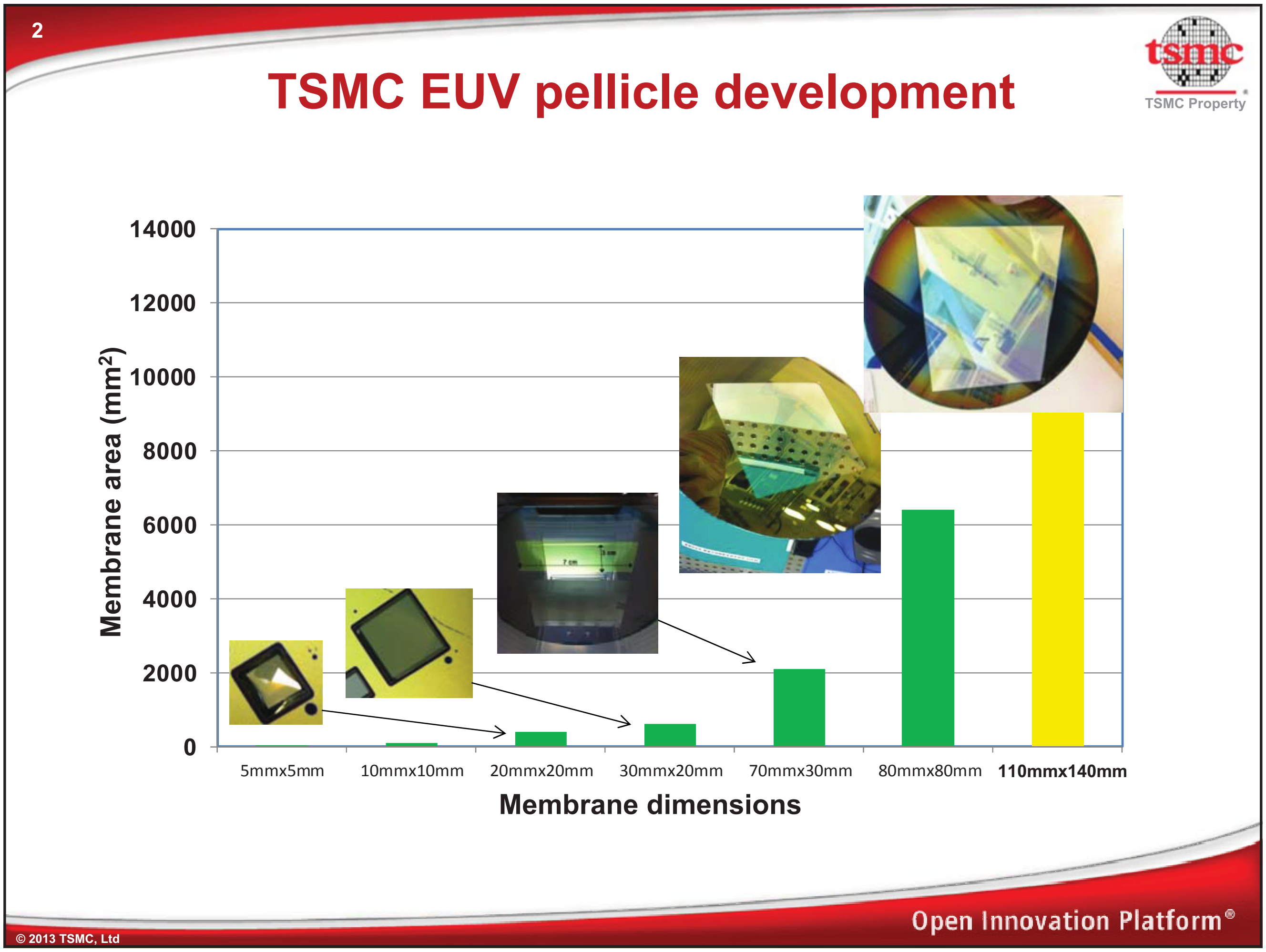
TSMC Property

(a) Conductive layer
(b) Low thermal expansion material
(c) Mo/Si multilayer
(d) Absorber

EUV Mask (downward facing) and associated Dual-Pod

Dual-Pod manufactured by Gudeng Precision Industrial Co.

Open Innovation Platform®



TSMC EUV pellicle development

TSMC Property

Open Innovation Platform®

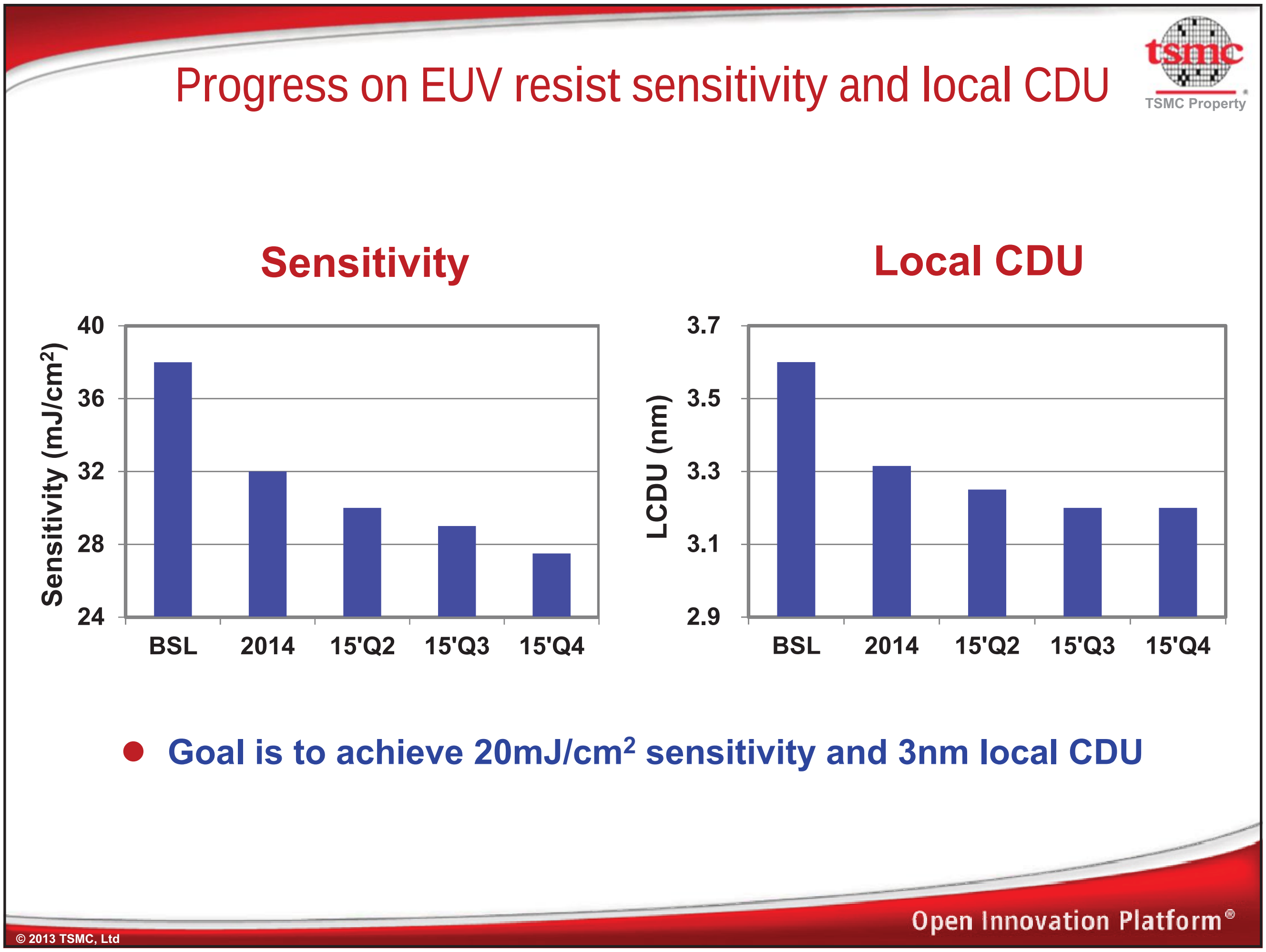
Pellicle Mounted on an EUV Mask Blank

TSMC Property

$Membrane\ thickness = 50nm$ $\qquad$ $Transmission = 85\%$

Membrane provided by ASML

Open Innovation Platform®



Progress on EUV resist sensitivity and local CDU

TSMC Property

Sensitivity

Local CDU

- Goal is to achieve $20 mJ/cm^2$ sensitivity and 3nm local CDU

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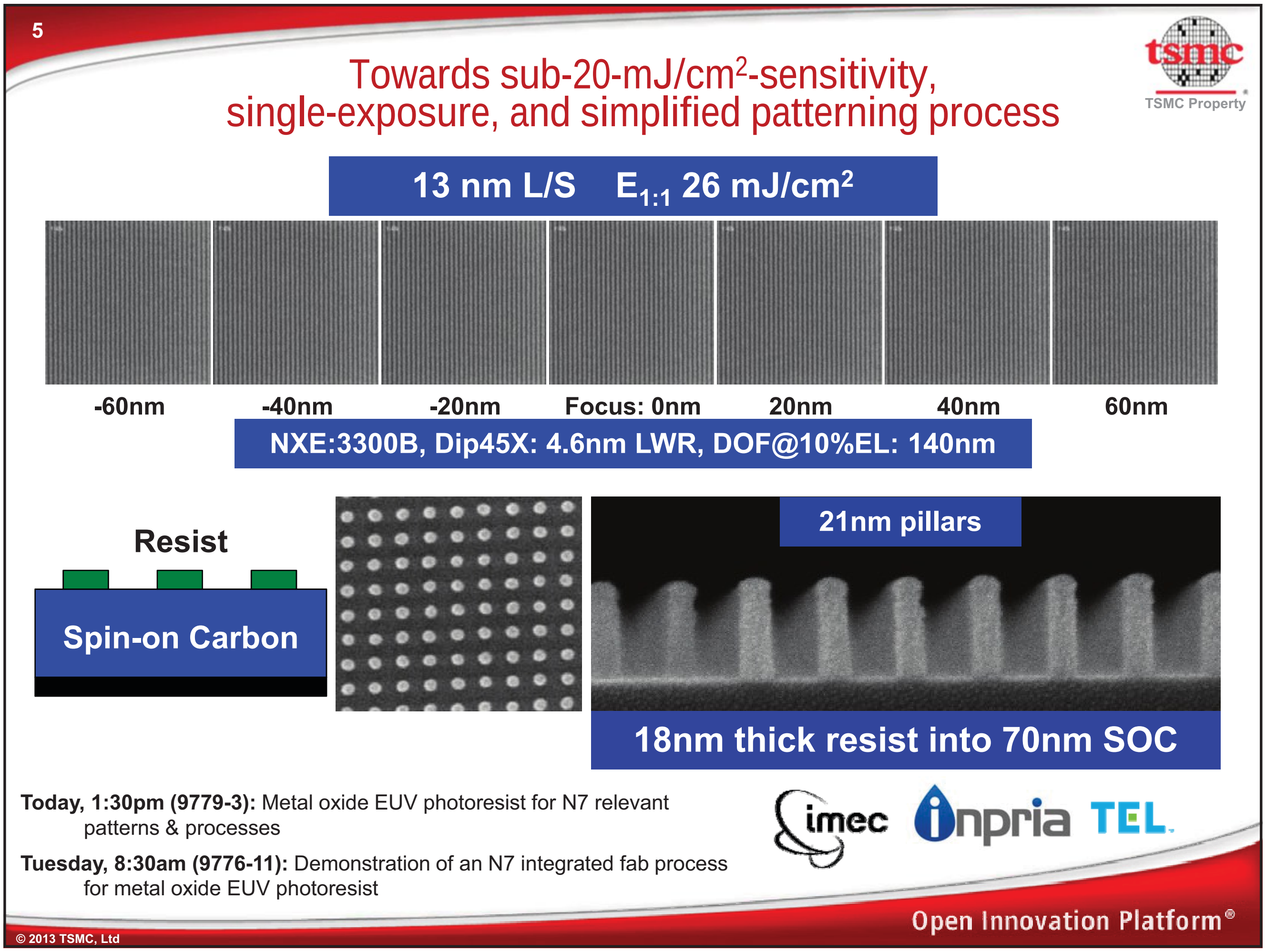

5

TSMC Property

Towards sub-20-mJ/cm^2-sensitivity, single-exposure, and simplified patterning process

13 nm L/S $E_{1:1}$ 26 mJ/cm^2

NXE:3300B, Dip45X: 4.6nm LWR, DOF@10%EL: 140nm

21nm pillars

18nm thick resist into 70nm SOC

Today, 1:30pm (9779-3): Metal oxide EUV photoresist for N7 relevant patterns & processes

Tuesday, 8:30am (9776-11): Demonstration of an N7 integrated fab process for metal oxide EUV photoresist

imec inpria TEL

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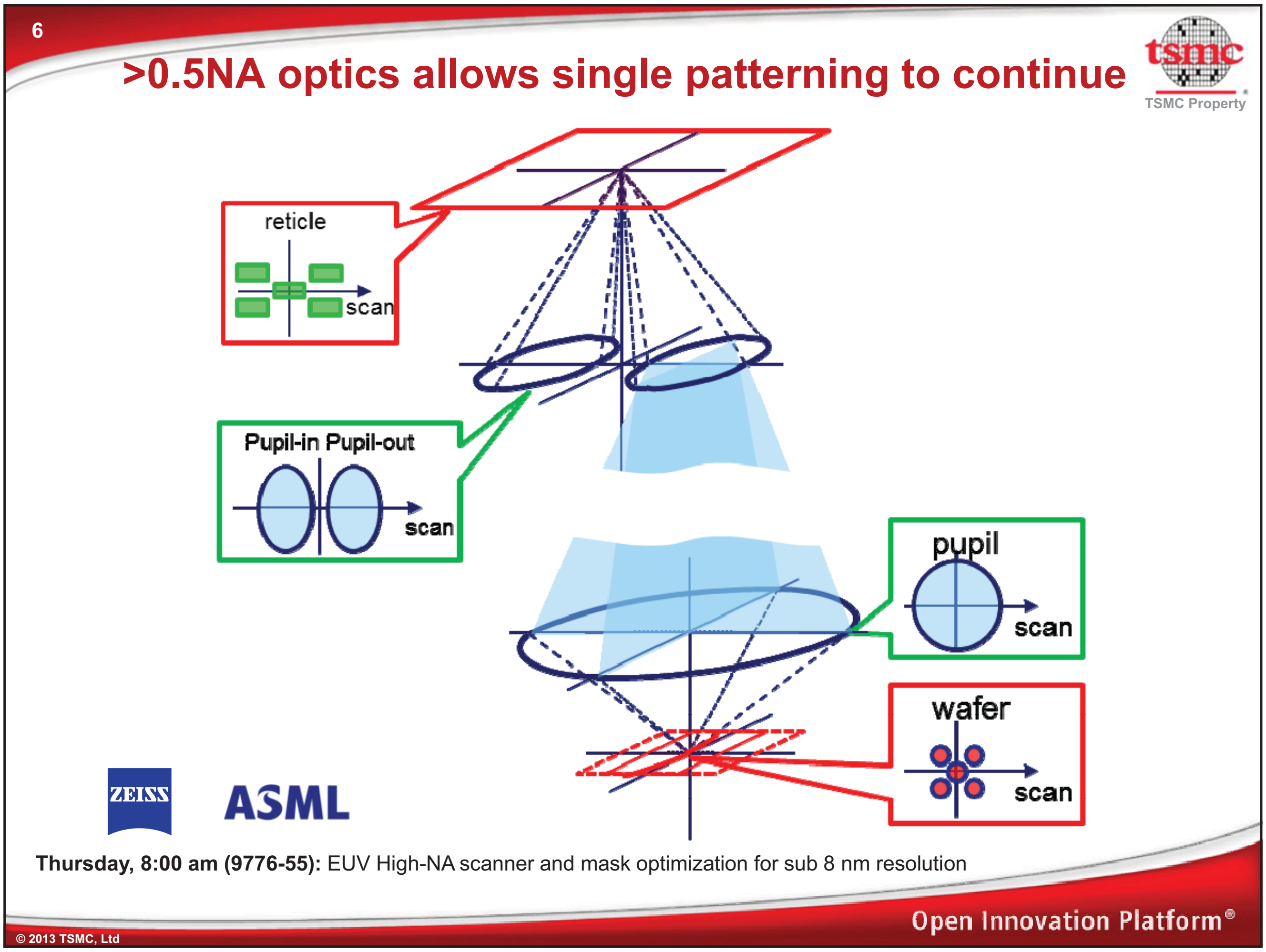
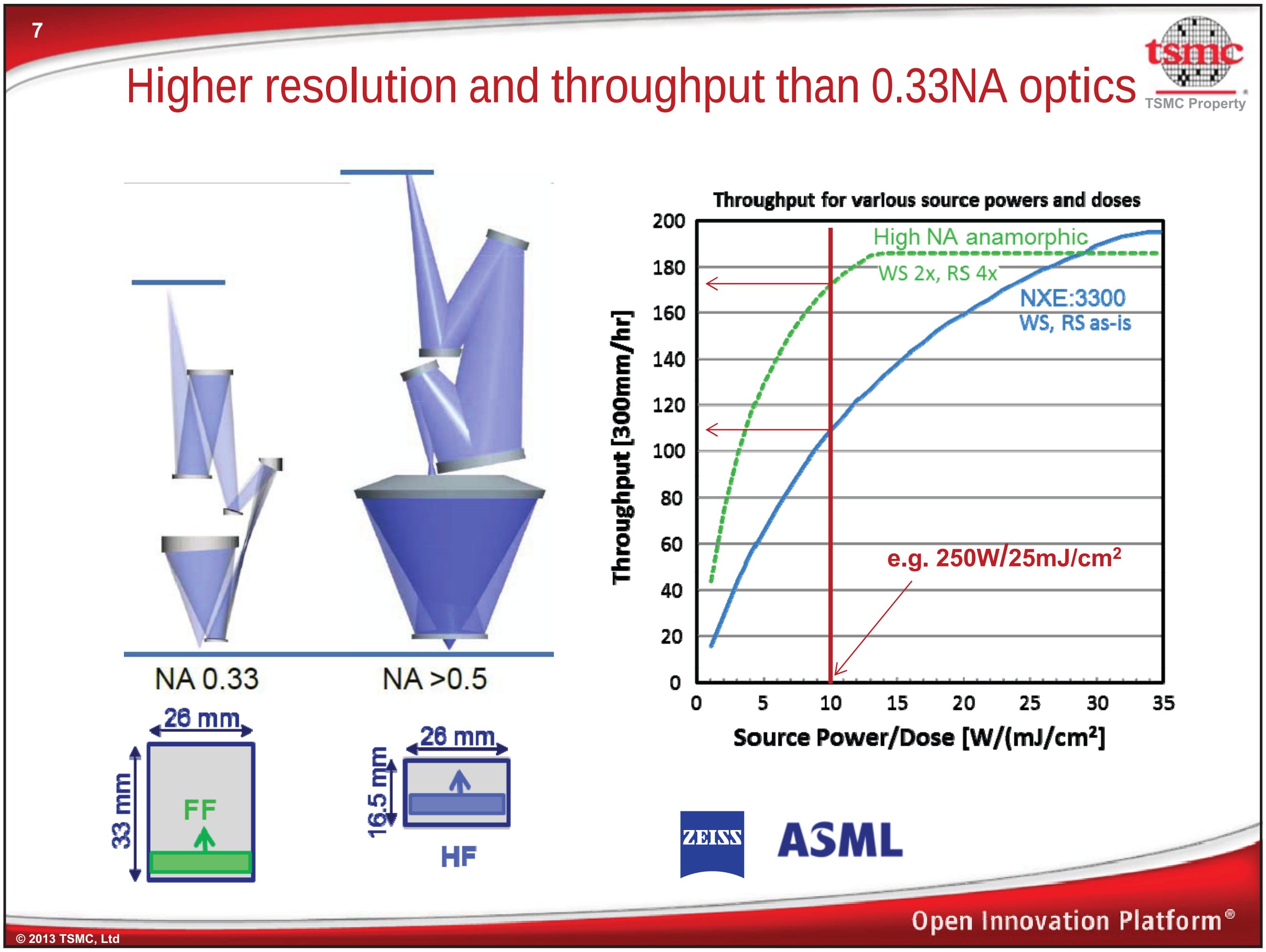


>0.5NA optics allows single patterning to continue

TSMC Property

Thursday, 8:00 am (9776-55): EUV High-NA scanner and mask optimization for sub 8 nm resolution

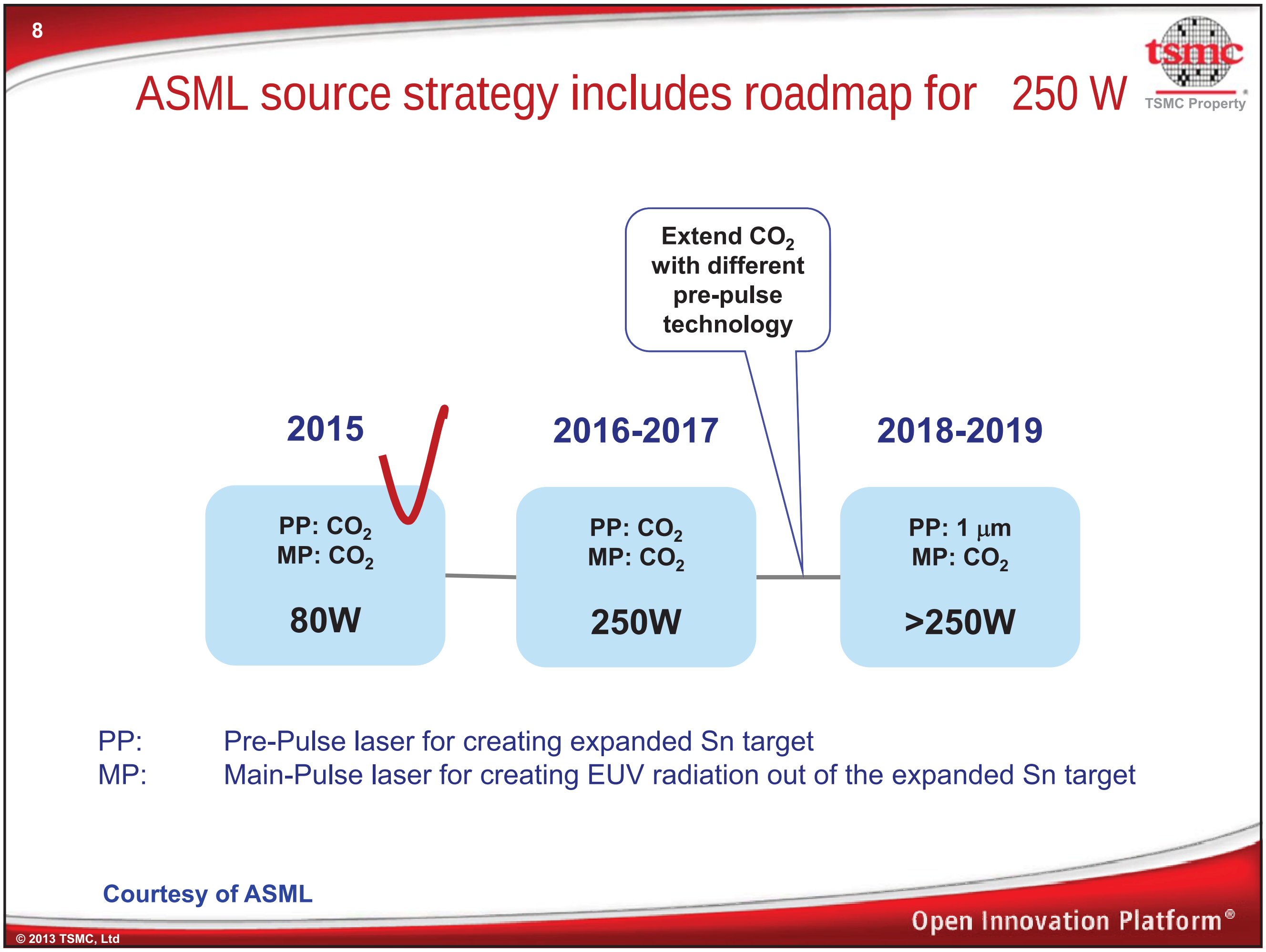
Open Innovation Platform®



Higher resolution and throughput than 0.33NA optics

TSMC Property

Open Innovation Platform®



ASML source strategy includes roadmap for 250 W

TSMC Property

Extend CO_2 with different pre-pulse technology

2015 ✓

PP: CO_2
MP: CO_2

80W

2016-2017

PP: CO_2
MP: CO_2

250W

2018-2019

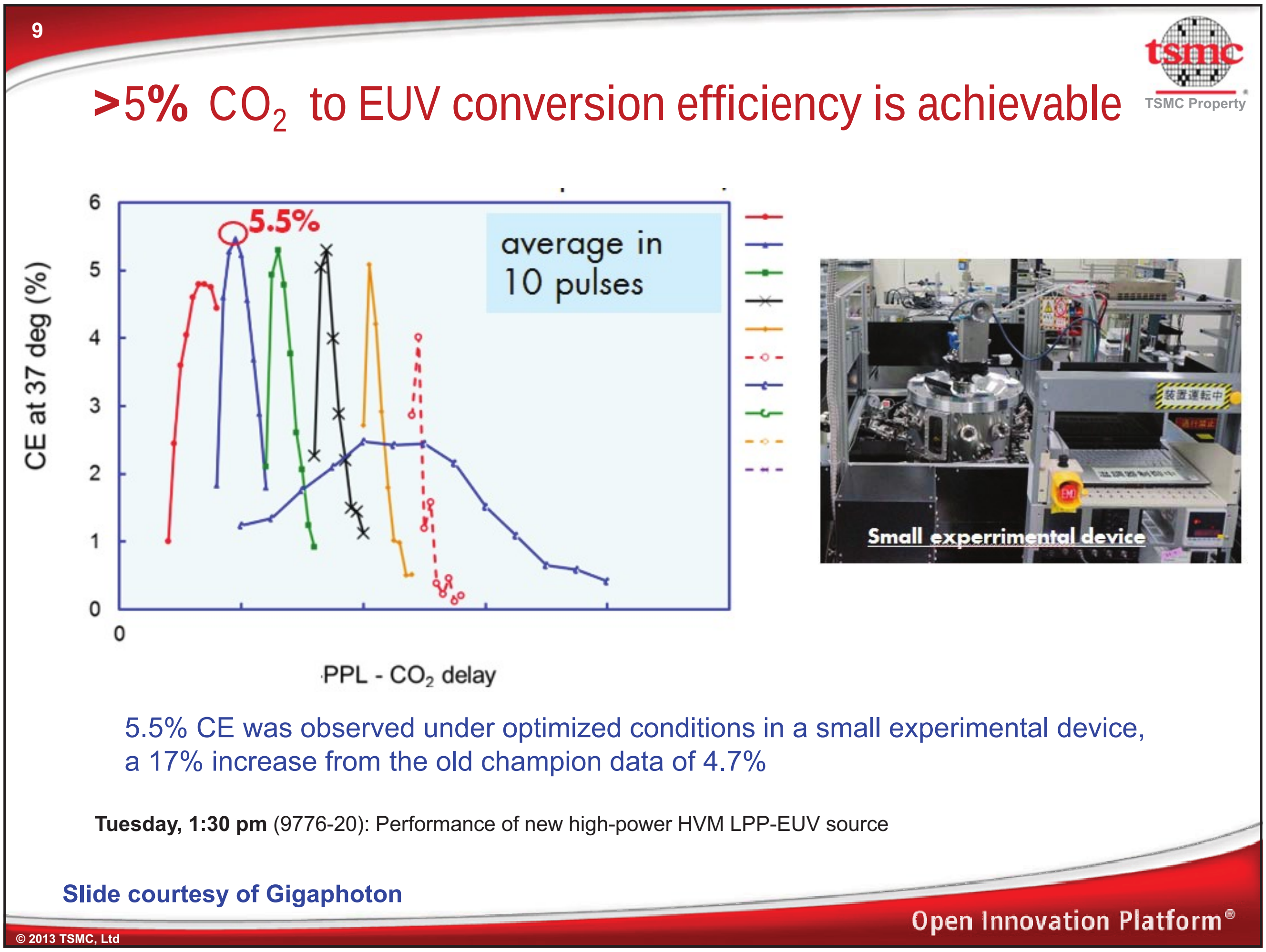
PP: 1 μm
MP: CO_2

>250W

PP:	Pre-Pulse laser for creating expanded Sn target
MP:	Main-Pulse laser for creating EUV radiation out of the expanded Sn target

Courtesy of ASML

Open Innovation Platform®



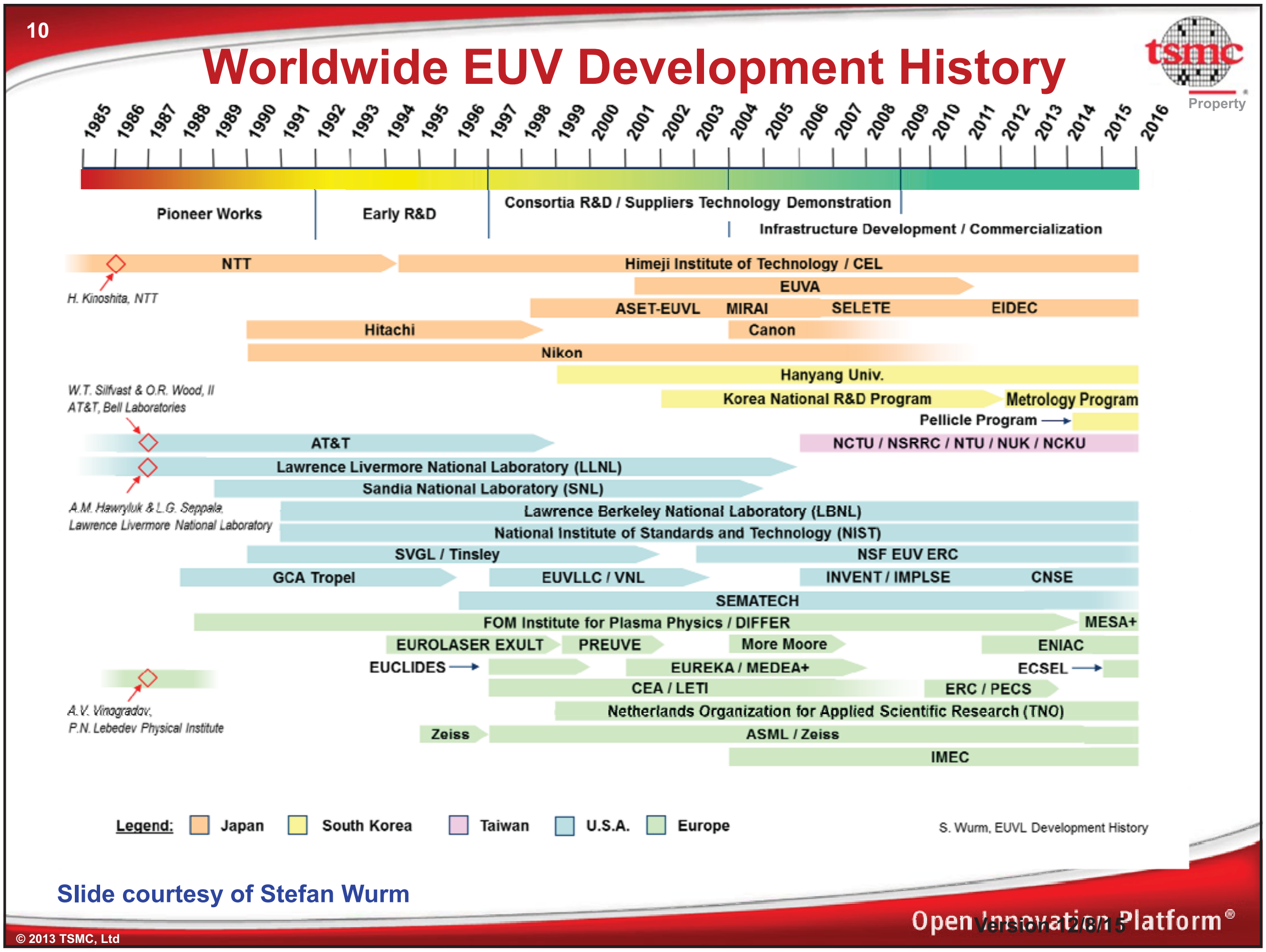
>5% CO_2 to EUV conversion efficiency is achievable

5.5% CE was observed under optimized conditions in a small experimental device, a 17% increase from the old champion data of 4.7%

Tuesday, 1:30 pm (9776-20): Performance of new high-power HVM LPP-EUV source

Slide courtesy of Gigaphoton

Open Innovation Platform®



10

Worldwide EUV Development History

tsmc Property

1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016

Pioneer Works | Early R&D | Consortia R&D / Suppliers Technology Demonstration | Infrastructure Development / Commercialization

NTT

Himeji Institute of Technology / CEL

H. Kinoshita, NTT

EUVA

ASET-EUVL

MIRAI

SELETE

EIDEC

Hitachi

Canon

Nikon

Hanyang Univ.

W.T. Silfvast & O.R. Wood, II
AT&T, Bell Laboratories

Korea National R&D Program

Metrology Program

Pellicle Program →

AT&T

NCTU / NSRRC / NTU / NUK / NCKU

Lawrence Livermore National Laboratory (LLNL)

Sandia National Laboratory (SNL)

A.M. Hawryluk & L.G. Seppala,
Lawrence Livermore National Laboratory

Lawrence Berkeley National Laboratory (LBNL)

National Institute of Standards and Technology (NIST)

SVGL / Tinsley

NSF EUV ERC

GCA Tropel

EUVLLC / VNL

INVENT / IMPLSE

CNSE

SEMATECH

FOM Institute for Plasma Physics / DIFFER

MESA+

EUROLASER EXULT

PREUVE

More Moore

ENIAC

EUCLIDES →

EUREKA / MEDEA+

ECSEL →

CEA / LETI

ERC / PECS

A.V. Vinogradov,
P.N. Lebedev Physical Institute

Netherlands Organization for Applied Scientific Research (TNO)

Zeiss

ASML / Zeiss

IMEC

Legend: 🟧 Japan 🟨 South Korea 🟪 Taiwan 🟦 U.S.A. 🟩 Europe

S. Wurm, EUVL Development History

Slide courtesy of Stefan Wurm

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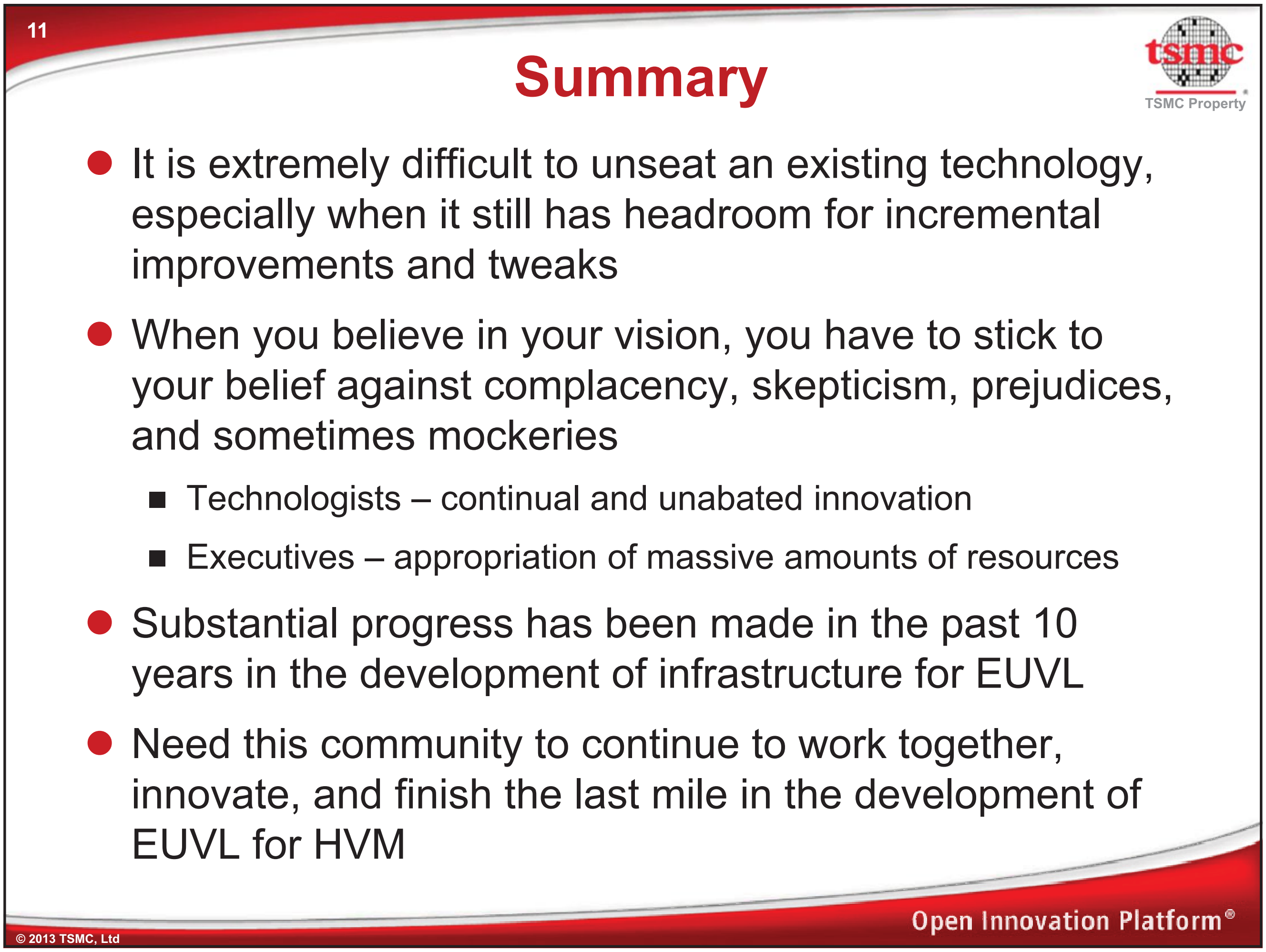
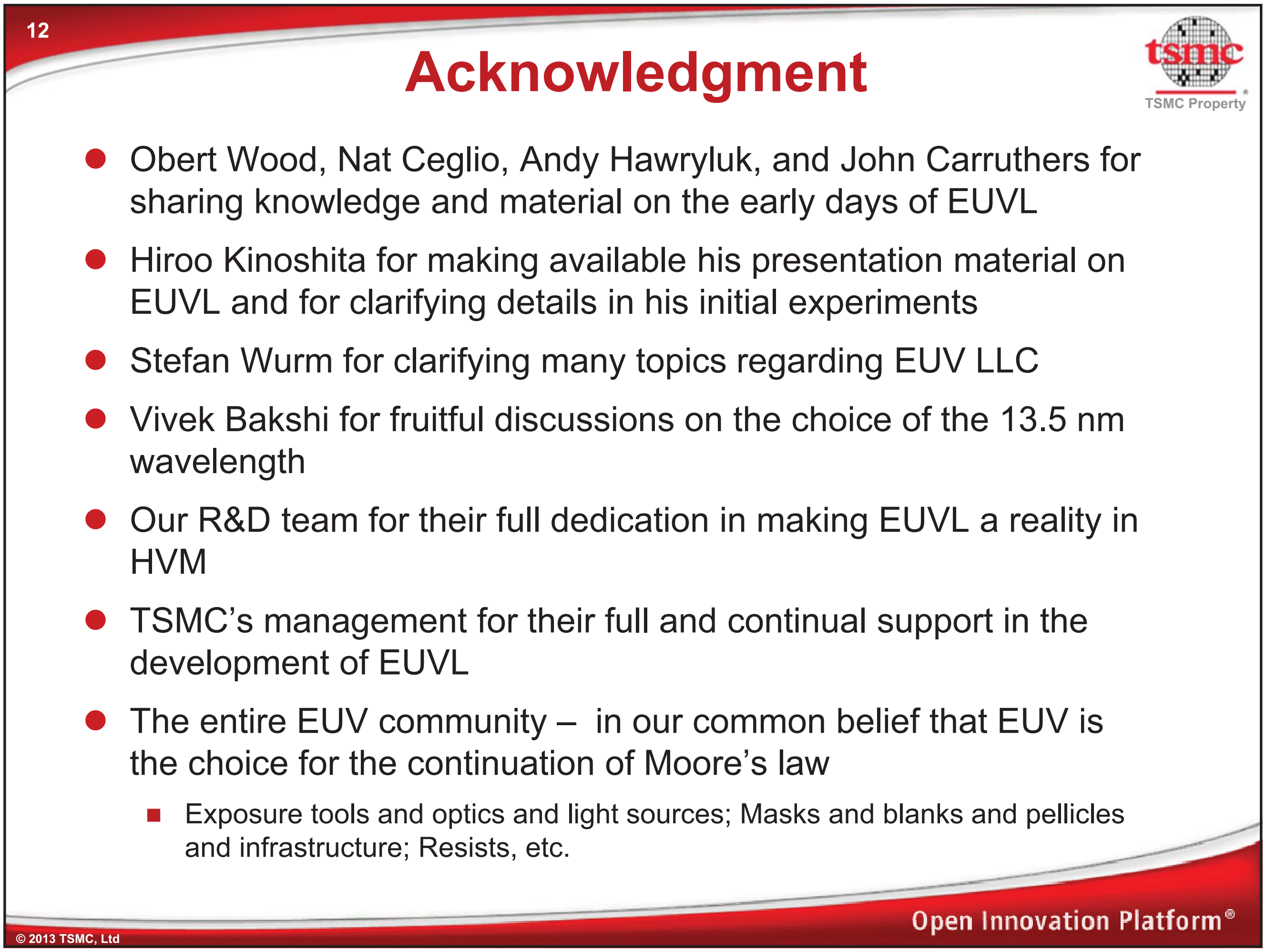


Summary

TSMC Property

- It is extremely difficult to unseat an existing technology, especially when it still has headroom for incremental improvements and tweaks
- When you believe in your vision, you have to stick to your belief against complacency, skepticism, prejudices, and sometimes mockeries
  - Technologists – continual and unabated innovation
  - Executives – appropriation of massive amounts of resources
- Substantial progress has been made in the past 10 years in the development of infrastructure for EUVL
- Need this community to continue to work together, innovate, and finish the last mile in the development of EUVL for HVM



Acknowledgment

TSMC Property

- Obert Wood, Nat Ceglio, Andy Hawryluk, and John Carruthers for sharing knowledge and material on the early days of EUVL
- Hiroo Kinoshita for making available his presentation material on EUVL and for clarifying details in his initial experiments
- Stefan Wurm for clarifying many topics regarding EUV LLC
- Vivek Bakshi for fruitful discussions on the choice of the 13.5 nm wavelength
- Our R&D team for their full dedication in making EUVL a reality in HVM
- TSMC's management for their full and continual support in the development of EUVL
- The entire EUV community – in our common belief that EUV is the choice for the continuation of Moore's law
    - Exposure tools and optics and light sources; Masks and blanks and pellicles and infrastructure; Resists, etc.

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