

## Albert Polman

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### Abstract

Albert Polman is a leading scientist in *nanophotonics: the control, understanding, and application of light at the nanoscale*.

Following his Ph.D. on ion-solid interactions and laser annealing in 1989, Albert Polman initiated an entirely new research field: optical doping using ion beams. This invention led to a very successful and highly cited (>200 articles, total >8000 citations, 20 papers >100 citations, h=50) research program on optics at the nanoscale, that includes studies on optical doping, light emission from silicon, spontaneous emission control, silicon quantum dots, rare-earth doped organics, plasmonics, and most recently, nanophotovoltaics. Over the past 20 years, Polman's group has been one of the leading groups in all these research directions.

Polman has given over 80 invited talks at international conferences, several of which as keynote or plenary speaker. He has organized several conferences in his field, and initiated a new Gordon Conference in the new research field of plasmonics, of which he is one of the leaders. Polman is member of many advisory boards and committees; he initiated the Center for Nanophotonics at the FOM-Institute AMOLF in 2005, and was appointed director of AMOLF in 2006. In recognition of his scientific achievements, Polman was appointed member of the Royal Netherlands Academy of Sciences in 2009.

### Key publications:

1. *A silicon-based electrical source of surface plasmon polaritons*, R.J. Walters, R.V.A. van Loon, I. Brunets, J. Schmitz and A. Polman, *Nature Materials* **9**, 21 (2010)
2. *Plasmonics for improved photovoltaic devices*, H.A. Atwater and A. Polman, *Nature Materials* **9**, 21 (2010)
3. *Nanowire plasmon excitation by adiabatic mode transformation*, E. Verhagen, M. Spasenović, A. Polman, and L. Kuipers, *Phys. Rev. Lett.* **102**, 203904 (2009).
4. *Purcell factor enhanced scattering from Si nanocrystals in an optical microcavity*, T. J. Kippenberg, A. L. Tchebotareva, J. Kalkman, A. Polman, and K. J. Vahala, *Phys. Rev. Lett.* **103**, 027406 (2009).
5. *Plasmonics applied*, A. Polman, *Science* **322**, 868 (2008)
6. *Plasmon slot waveguides: towards chip-scale propagation with subwavelength-scale localization*, J.A. Dionne, L. Sweatlock, H.A. Atwater, and A. Polman, *Phys. Rev. B* **73**, 035407 (2006) (**100 citations**)
7. *Measuring and modifying the spontaneous emission rate of erbium near an interface*, E. Snoeks, A. Lagendijk, and A. Polman, *Phys. Rev. Lett.* **74**, 2459 (1995). (**123 citations**)
8. *Erbium implanted thin film photonic materials*, A. Polman, *J. Appl. Phys.* **82**, 1 (1997). (**644 citations**)
9. *Room-temperature electroluminescence from Er-doped crystalline Si*, G. Franzó, F. Priolo, S. Coffa, A. Polman, and A. Carnera, *Appl. Phys. Lett.* **64**, 2235 (1994). (**279 citations**)
10. *Defect-related versus excitonic visible light emission from ion beam synthesized Si nanocrystals in SiO<sub>2</sub>*, K.S. Min, K.V. Shcheglov, C.M. Yang, H.A. Atwater, M.L. Brongersma and A. Polman, *Appl. Phys. Lett.* **69**, 2033 (1996). (**317 citations**)

Below, an overview is given of Polman's key scientific achievements.

### Optical doping

Following his Ph.D. research at the FOM-Institute AMOLF in Amsterdam on laser- and ion-beam induced phase transformations in silicon (1985-1989), Albert Polman started working on optical materials when he was appointed as a post-doctoral researcher at AT&T Bell Laboratories. Here, he invented the concept of "optical doping": the incorporation and optical activation of optically active ions in thin-film materials by ion implantation. He initiated experiments on erbium implantation into a range of dielectric materials and studied the damage annealing and activation of optical dopants. He studied optical interactions between rare earth ions that result from Förster energy transfer, and studied the coupling of rare earth electronic states to matrix defects. He was one of the first to carry out optical spectroscopy in optical waveguides, taking advantage of the high continuous-wave pump laser intensity that can be achieved in these structures. He identified cooperative upconversion as the main gain-limiting effect in highly doped optical amplifiers. The understanding of the optical properties of highly rare earth doped thin films eventually led to the

fabrication of the world's smallest erbium-doped planar optical amplifier, a concept that was commercialized by Symmorphix, a company in Silicon Valley, in 2001. Most recently, Polman used his knowledge of the optical doping technique in a collaboration with the group of Vahala at CALTECH, developing the world's smallest rare earth doped microcavity laser on silicon, based on an ultra-high Q Er-implanted toroidal silica cavity.

### Key publications

1. *Erbium implanted thin film photonic materials*, A. Polman, J. Appl. Phys. **82**, 1 (1997). **(644 citations)**
2. *Optical doping of waveguide materials by MeV Er implantation*, A. Polman, D.C. Jacobson, D.J. Eaglesham, R.C. Kistler and J.M. Poate, J. Appl. Phys. **70**, 3778 (1991). **(114 citations)**
3. *Photoluminescence characterization of Er-implanted Al<sub>2</sub>O<sub>3</sub> films*, G.N. van den Hoven, E. Snoeks, A. Polman, J.W.M. van Uffelen, Y.S. Oei, and M.K. Smit, Appl. Phys. Lett. **62**, 3065 (1993). **(119 citations)**
4. *Net optical gain at 1.53  $\mu$ m in Er-doped Al<sub>2</sub>O<sub>3</sub> waveguides on silicon*, G.N. van den Hoven, A. Polman, C. van Dam, J.W.M. van Uffelen, and M.K. Smit, Appl. Phys. Lett. **68**, 1886 (1996). **(117 citations)**
5. *Ultra-low threshold erbium-implanted toroidal microlaser on silicon*, A. Polman, B. Min, J. Kalkman, T.J. Kippenberg, and K.J. Vahala, Appl. Phys. Lett. **84**, 1037 (2004). **(57 citations)**

### Light from Er-doped silicon

Following his initial studies on optical doping of dielectrics, Polman changed focus to the optical doping of silicon, where he first pioneered a new non-equilibrium solid-state epitaxial growth method to incorporate high concentrations of the insoluble rare earth ions into the semiconductor host. He then studied the opto-electronic coupling between the 4f electronic states of rare earth ions and the rare-earth related electronic defect states in the semiconductor bandgap. Together with his collaborators from the University of Catania, he identified an Er-O cluster configuration that lead to optimum light emission from Er-doped Si. From temperature dependent spectroscopy he identified energy backtransfer through this defect state to be the main quenching mechanism for the luminescence of Er in Si and determined the optically active solubility limit of the defect complex. Subsequently, with his collaborators, he developed the first room-temperature light emitting diode based on Si:Er. Altogether, Polman is the pioneer of rare earth doping of thin film dielectrics and semiconductors, and of the study of optical interactions in these materials. Indeed, many research groups worldwide have followed his group on this topic.

### Key publications

6. *Incorporation of high concentrations of erbium in crystal silicon*, A. Polman, J.S. Custer, E. Snoeks, and G.N. van den Hoven, Appl. Phys. Lett. **62**, 507 (1993). **(78 citations)**
7. *Temperature dependence and quenching processes of the intra-4f luminescence of Er in crystalline Si*, S. Coffa, G. Franzó, F. Priolo, A. Polman, and R. Serna, Phys. Rev. B **49**, 16313 (1994). **(198 citations)**
8. *Room-temperature electroluminescence from Er-doped crystalline Si*, G. Franzó, F. Priolo, S. Coffa, A. Polman, and A. Carnera, Appl. Phys. Lett. **64**, 2235 (1994). **(273 citations)**
9. *Erbium in crystal silicon: Optical activation, excitation, and concentration limits*, A. Polman, G.N. van den Hoven, J.S. Custer, J.H. Shin, and R. Serna, J. Appl. Phys. **77**, 1256 (1995). **(91 citations)**
10. *Energy backtransfer and infrared photocurrent in erbium-doped silicon p-n junctions*, N. Hamelin, P.G. Kik, J.F. Suyver, K. Kikoin, A. Polman, A. Schönecker, and F.W. Saris, J. Appl. Phys. **88**, 5381 (2000). **(38 citations)**

### Spontaneous emission controlled

Fermi's Golden Rule tells that the emission rate from an optical emitter is determined by the final optical density of states. In order to achieve control over this property, in 1994 Polman started experiments on modifying the dielectric environment around optical emitters. These experiments became possible because the optical doping technique developed by Polman enables placement of optical dopants with a spatial control much smaller than the optical wavelength. By modulating the local density of states near a dielectric interface he was able to demonstrate variations in the radiative decay rate of rare earth ions, transition metals, and most recently Si quantum dots. He further explored this concept to identify non-radiative decay processes, which are often difficult or impossible to independently determine. In collaboration with Sandia National Laboratories Polman was the first to demonstrate modified spontaneous emission in a three-dimensional photonic crystal with a full photonic bandgap, using a Si photonic woodpile structure. In subsequent work, he demonstrated that Förster energy transfer is not affected by the local density

of states in the optical spectral range. Most recently, Polman, together with his collaborators at CALTECH and MPQ (Münich) demonstrated experimentally and theoretically that scattering in a high-Q optical microcavity occurs preferentially into the cavity modes at a rate that is controlled by the Purcell Factor, in a similar way that this factor controls spontaneous emission.

### Key publications

11. *Measuring and modifying the spontaneous emission rate of erbium near an interface*, E. Snoeks, A. Lagendijk, and A. Polman, *Phys. Rev. Lett.* **74**, 2459 (1995). (106 citations)
12. *Local optical density of states in SiO<sub>2</sub> spherical microcavities: theory and experiment*, M.J.A. de Dood, L.H. Slooff, A. Moroz, A. van Blaaderen, and A. Polman, *Phys. Rev. A.* **64**, 33807 (2001). (27 citations)
13. *Modified spontaneous emission from erbium doped photonic layer-by-layer crystals*, M.J.A. de Dood, A. Polman, and J.G. Fleming, *Phys. Rev. B* **67**, 115106 (2003). (16 citations)
14. *Förster transfer and the local density of states in erbium-doped silica*, M.J.A. de Dood, J. Knoester, A. Tip, and A. Polman, *Phys. Rev. B* **71**, 115106 (2005). (15 citations)
15. *Purcell factor enhanced scattering from Si nanocrystals in an optical microcavity*, T. J. Kippenberg, A. L. Tchebotareva, J. Kalkman, A. Polman, and K. J. Vahala, *Phys. Rev. Lett.* **103**, 027406 (2009). (0 citations)

### Ion solid interactions: nanoscale continuum mechanics

As a side track along optical experiments, Polman has pursued research to obtain insight in the fundamentals of ion-solid interactions. Indeed, due to this knowledge on ion implantation, he was able to fabricate optical materials or structures that are otherwise impossible to make. Using an *in-situ* wafer-curvature measurement technique, that probes mechanical stress in a thin film during ion irradiation, Polman and his collaborator Volkert were able to distinguish, on a microscopic scale, the effects of radiation-induced Newtonian viscous flow, anisotropic deformation, and point defect generation and annihilation that all occur during ion irradiation of silica glass. He was the first to relate macroscopic parameters to microscopic phenomena that occur in the picosecond thermal spike of the nanoscale ion track. Most recently, with his collaborators at Groningen University, he identified the role of capillary forces in shape changes of nanoscale objects under ion irradiation.

### Key publications

16. *Densification, anisotropic deformation and plastic flow of SiO<sub>2</sub> during MeV heavy ion irradiation*, E. Snoeks, A. Polman, and C.A. Volkert, *Appl. Phys. Lett.* **65**, 2487 (1994). (54 citations)
17. *MeV ion irradiation induced creation and relaxation of mechanical stress in silica*, E. Snoeks, T. Weber, A. Cacciato, and A. Polman, *J. Appl. Phys.* **78**, 4723 (1995) (62 citations)
18. *Colloidal ellipsoids with continuously variable shape*, E. Snoeks, A. van Blaaderen, T. van Dillen, C.M. van Kats, M.L. Brongersma, and A. Polman, *Adv. Mater.* **12**, 1511 (2000). (56 citations)
19. *Ion beam induced anisotropic deformation of silica at 300 keV*, T. van Dillen, A. Polman, C. van Kats and A. van Blaaderen, *Appl. Phys. Lett.* **83**, 4315 (2003), (27 citations)
20. *Aligned gold nanorods in silica made by ion irradiation of core-shell colloidal particles* S. Roorda, T. van Dillen, A. Polman, C. Graf, A.M. Vredenberg, A. van Blaaderen, and B. Kooi, *Adv. Mater.* **16**, 235 (2004). (49 citations)

### Silicon quantum dots: excitons versus defects

Quantum dots are known to exhibit excitonic emission, with the wavelength dependent by the size. While this is well established for compound semiconductors, studies on light emission from quantum dots made of the indirect bandgap semiconductor Si were initially scarce. Achieving light emission from silicon nanostructures is one of the holy grails of opto-electronic technology, and Polman's group has played a key role in establishing this research field worldwide. Together with the group of Atwater at CALTECH, Polman pioneered a novel way to fabricate optically active Si quantum dots in a SiO<sub>2</sub> matrix, using ion implantation, annealing and a suitable passivation step; their two key papers are very highly cited. Together with collaborators at the University of Catania, Polman was the first to demonstrate energy transfer between quantum confined excitonic states in Si nanostructures and the 4f electronic shells of the rare earth ions bringing together the fields of optical doping and quantum confined exciton emission in Si.

### Key publications

21. *Room-temperature luminescence from Er-implanted semi-insulating polycrystalline silicon*, S. Lombardo, S.U. Campisano, G.N. van den Hoven, A. Cacciato, and A. Polman, *Appl. Phys. Lett.* **63**, 1941 (1993). (**86 citations**)
22. *Defect-related versus excitonic visible light emission from ion beam synthesized Si nanocrystals in SiO<sub>2</sub>*, K.S. Min, K.V. Shcheglov, C.M. Yang, H.A. Atwater, M.L. Brongersma and A. Polman, *Appl. Phys. Lett.* **69**, 2033 (1996). (**295 citations**)
23. *The role of quantum-confined excitons vs defects in the visible luminescence of SiO<sub>2</sub> films containing Ge nanocrystals*, K.S. Min, K.V. Shcheglov, C.M. Yang, Harry A. Atwater, M.L. Brongersma, and A. Polman, *Appl. Phys. Lett.* **68**, 2511 (1996). (**148 citations**)
24. *Tuning the emission wavelength of Si nanocrystals in SiO<sub>2</sub> by oxidation*, M.L. Brongersma, A. Polman, K.S. Min, E. Boer, T. Tambo, and H.A. Atwater, *Appl. Phys. Lett.* **72**, 2577 (1998). (**146 citations**)
25. *Strong exciton-erbium coupling in Si nanocrystal-doped SiO<sub>2</sub>*, P.G. Kik, M.L. Brongersma, and A. Polman, *Appl. Phys. Lett.* **76**, 2325 (2000). (**158 citations**)

### Rare-earth doped organic materials

Polymers play an important role in integrated optics, and there is great interest in active polymers for waveguide amplifiers, lasers and LEDs. Inspired by his earlier work on rare-earth doping of inorganic dielectrics and semiconductors, Polman initiated a research program together with groups at Twente University (Van Veggel, Reinhoudt) and Cambridge University (Friend) to synthesize rare-earth doped complexes, incorporate them in polymer hosts, and prove optical functionality. The collaboration resulted in the realization of optically active Er- and Nd-doped organic cage complexes, in which the rare earth was sensitized using either the cage itself or an attached lissamine sensitizer complex. Using the lissamine-sensitized complex, an LED was fabricated, and the first infrared polymer LED was demonstrated operating at 1.3  $\mu\text{m}$ . The project on rare earth doped polymers lead to 5 publications, that all were very well cited.

26. *Optical properties of erbium-doped polydentate organic cage complexes*, L. H. Slooff, A. Polman, M. P. Oude Wolbers, F.C.J.M. van Veggel, D. Reinhoudt and J. W. Hofstraat, *J. Appl. Phys.* **83**, 497 (1998) (**115 citations**)
27. *Sensitized near-infrared luminescence from polydentate triphenylene-functionalized Nd<sup>3+</sup>, Yb<sup>3+</sup> and Er<sup>3+</sup> complexes*, S.I. Klink, G.A. Hebbink, L. Grave, F.C.J.M. van Veggel, D.N. Reinhoudt, L.H. Slooff, A. Polman and J.W. Hofstraat, *J. Appl. Phys.* **86**, 1181 (1999) (**88 citations**)
28. *Optical properties of lissamine functionalized Nd<sup>3+</sup> complexes in polymer waveguides and solution*, L.H. Slooff, A. Polman, S.I. Klink, G.A. Hebbink, L. Grave, F.C.J.M. van Veggel, D.N. Reinhoudt and J.W. Hofstraat, *Optical Materials* **14**, 101 (2000) (**59 citations**)
29. *Near-infrared electroluminescence of polymer light-emitting diodes doped with a lissamine-sensitized Nd<sup>3+</sup> complex*, L.H. Slooff, A. Polman, F. Cacialli, R. H. Friend, G.A. Hebbink, F.C.J.M. van Veggel and D.N. Reinhoudt, *Appl. Phys. Lett.* **78**, 2122 (2001) (**70 citations**)
30. *Rare earth doped polymer waveguides and LEDs*, L.H. Slooff, A. Polman, S.I. Klink, L. Grave, F.C.J.M. van Veggel and J.W. Hofstraat, *J. Appl. Phys.* **91**, 3955 (2002) (**114 citations**)

### Plasmonics: optics at the nanoscale

Most recently, Polman has redirected his group's research activities towards plasmonics, the manipulation of light using metallic nanostructures. He developed a near-field optical microscopy imaging technique to study the propagation, damping and dispersion of surface plasmon polaritons at length scales well below the diffraction limit. Using specially designed plasmon tapers he demonstrated, together with his collaborator Kuipers, nanofocusing of light into volumes as small as  $\lambda/16$  and demonstrated non-linear optical effects in these plasmonic hot spots using upconversion in erbium ion. Polman's group pioneered the use of cathodoluminescence imaging spectroscopy as a technique to study the dispersion of surface plasmon polaritons at nanoscale resolution. He observed localized modes and strong dispersion in Ag nanowires and nanoresonators using this technique, and probed the local plasmonic density of states. Using electron-beam lithography he fabricated nanoparticle waveguides in which light is guided by dipole coupling between the metal nanoparticles observed an unexpected behavior in the dispersion of these waveguides, that leads to frequency tunable localization of energy along the arrays. Polman further studied the coupling between plasmonic nanoparticles and optical emitters such as Si quantum dots and erbium ions. He demonstrated that the strong local field enhancements in engineered metal nanostructures leads to enhanced and polarization-controlled

photoluminescence as well as electroluminescence. To demonstrate these effects at the smallest possible scale he developed a molecular templating technique using DNA to assemble plasmonic nanostructures with unique (bio-)sensing properties. Most recently, his group has expanded its activities into the area of plasmonic photovoltaics. He has developed the fundamental design rules for plasmon enhanced photocurrent collection from solar cells, enabling the design and fabrication of an entirely new class of ultra-thin film solar cells.

### Key publications

31. *Highly confined electromagnetic fields in arrays of strongly coupled Ag nanoparticles*, L.A. Sweatlock, S.A. Maier, H.A. Atwater, J.J. Penninkhof, and A. Polman, *Phys. Rev. B* **71**, 235408 (2005) **(70 citations)**
32. *Polarization-selective plasmon-enhanced Si quantum dot luminescence*, H. Mertens, J.S. Biteen, H.A. Atwater, and A. Polman, *Nano Lett.* **6**, 2622 (2006). **(38 citations)**
33. *Plasmon slot waveguides: towards chip-scale propagation with subwavelength-scale localization*, J.A. Dionne, L. Sweatlock, H.A. Atwater, and A. Polman, *Phys. Rev. B* **73**, 035407 (2006) **(100 citations)**
34. *Tunable nanoscale localization of energy on plasmon particle arrays*, R. de Waele, A.F. Koenderink, and A. Polman, *Nano Lett.* **7**, 2004 (2007), also highlighted in *Nature* **448**, 141 (2007). **(22 citations)**
35. *Complex response and polariton-like dispersion splitting in periodic metal nanoparticle chains*, A.F. Koenderink and A. Polman, *Phys. Rev. B* **74**, 033402 (2006). **(40 citations)**
36. *Plasmon-based nanolenses placed on a well-defined DNA template*, S. Bidault, J. Garcia de Abajo, and A. Polman, *J. Amer. Chem. Soc.* **130**, 2750 (2008). **(15 citations)**
37. *Design principles for particle plasmon enhanced solar cells*, K.R. Catchpole and A. Polman, *Appl. Phys. Lett.* **93**, 191113 (2008). **(15 citations)**
38. *Nanowire plasmon excitation by adiabatic mode transformation*, E. Verhagen, M. Spasenović, A. Polman, and L. Kuipers, *Phys. Rev. Lett.* **102**, 203904 (2009). **(7 citations)**
39. *A silicon-based electrical source of surface plasmon polaritons*, R.J. Walters, R.V.A. van Loon, I. Brunets, J. Schmitz and A. Polman, *Nature Materials* **9**, 21 (2010) **(1 citation)**

### Scientific leadership

As is clear from the above descriptions, Polman has regularly changed research topic over the past years, initiating new research themes every time. Every time, in starting new research topics he took advantage of knowledge and techniques developed in previous work. For many of these new topics he proved to be a leader. Polman is acknowledged worldwide as the pioneer of the “optical doping” technique; his review article on his work has been cited nearly 600 times. His work on Er-doped Si, together with the Catania group, lead to the most highly cited papers in this field. Similarly, his work with Atwater on Si quantum dots lead to the most highly cited papers in that research field. In the field of ion beam modification of materials, Polman was a five-time invited speaker at the bi-annual conference series (IBMM) on this topic. He is one of the leaders of the plasmonics field as testified by several interviews and opinion articles published in *Nature* and *Science*. He has given over 80 invited talks at international conferences. Polman is one of the initiators and leaders of the new field of plasmonics. Together with his colleague Atwater he took the initiative to start a Gordon Research Conference on this topic, Polman chairing the first one in 2006. Polman gave plenary presentations on plasmonics at CLEO/QELS (San Jose, 2008) and Euromat (Glasgow, 2009), and invited keynote presentations at CLEO/QELS (Münich, 2009) and SPIE (San Diego, 2009).

Polman’s leadership is also testified by his initiatives to organize international conferences in his field. He co-chaired symposia at MRS conferences in 1994, 1995, 1997, and 2003. He chaired the IBMM conference in 1998, and was co-chair of the MRS Spring Meeting in 2003. In the Netherlands, Polman initiated several national research programs and facilities: the FOM Program Photon Physics in Optical Materials, the NANONED Flagship Nanophotonics, the Amsterdam nanoCenter cleanroom, and a national facility for Nanofabrication for Nanophotonics. In 2005 he established the Center for Nanophotonics at the FOM-Institute AMOLF, a research center with over 50 nanophotonics scientists.

In recognition of his scientific leadership, Polman was appointed director of the FOM-Institute AMOLF in 2006. As a director, Polman has taken initiatives to concentrate AMOLF’s research program in two main directions: Nanophotonics and Physics of Biomolecular Physics. Under his guidance, the institute underwent an international panel evaluation in 2006, at which the institute as a whole and each of the research programs of AMOLF were rated as excellent. Most recently,

Polman has successfully steered the institute into a direction where high-quality fundamental research is combined with effective initiatives to achieve knowledge transfer to industry and society. In recognition of his scientific research, Polman was appointed member of the Royal Netherlands Academy of Sciences in 2009.

### Key publications

40. *Photonic materials - Teaching silicon new tricks*, A. Polman, *Nature Materials* **1**, 10 (2002)
41. *Plasmonics applied*, A. Polman, *Science* **322**, 868 (2008)

### Education, teaching

Polman is associated with the University of Utrecht as a professor of nanophotonics. In 1998, he gave his inaugural lecture, entitled “The Optical Chord” demonstrating the relation between optical phenomena in nanomaterials and the musical scale. He developed a new teaching method for his materials science class, in which lectures are composed of 6 “lecture clips” of 15 min each, based on the presumption that the typical student’s attention span is roughly 15 min. Polman presented the method first at an MRS symposium in 1997 and then published it in the *Journal of Materials Education*. It has served as an example to many other teachers. The students’ ratings for Polman’s courses were always between 8 and 9 (on a 1-10 scale).

### Key publication

42. *15 minute clips on materials engineering*; A. Polman, *J. Mater. Education* **20**, 119 (1998)

### Inventions, knowledge transfer to society and industry

Carrying out fundamental research and at the same time collaborating with industrial partners and transferring knowledge has always been a key part of Polman’s work. In the past years he has interacted with the following industrial partners: AT&T Bell Laboratories, Symmorphix, ST Microelectronics, Intel Corporation, Philips, Shell, FEI, TNO, ECN, KPN, AKZO-Nobel. He has published papers or filed patents with all of these companies. Polman, is co-inventor on five patents, four of which in collaboration with industrial partners.

### Patents

43. *Apparatus comprising an optical gain device, and method of producing the device*, G.E. Blonder, D.C. Jacobson, R.C. Kistler, J.M. Poate and A. Polman (with AT&T, 1991)
44. *Electro-luminescent material, solid state electro-luminescent device and process for fabrication thereof*, S.U. Campisano, S. Lombardo, G. Ferla, G.N. van den Hoven and A. Polman (with ST Microelectronics, 1993)
45. *Infrared detector device of semiconductor material and manufacturing process thereof*, A. Polman, N. Hamelin, P.G. Kik, S. Coffa, M. Saggio, and F. Frisina (with ST Microelectronics, 1999)
46. *Silver-sensitized erbium-doped planar waveguide amplifier*, C. Strohhofer, and A. Polman (with Symmorphix, 2003)
47. *Photovoltaic cell with surface plasmon resonance generating nano-structures*, K.R. Catchpole, A. Polman, European Patent Application, number 08103442.3 (2008).

### (Inter-)national scientific collaborations

Polman’s group has always been very strong in establishing links with other academic partners. He has collaborated (and published papers) with the following academic institutions: Utrecht University, Groningen University, Leiden University, University of Amsterdam, Eindhoven University of Technology, Technical University Twente, Technical University Delft, Research Center Jülich, University of Catania, Cambridge University, and California Institute of Technology. His group is also part of two major initiatives in the United States: Multidisciplinary Research Initiative (MURI) on Plasmonics (with CALTECH, Harvard University, the University of California at Los Angeles (UCLA), the University of San Diego and Berkeley University), and the Global Climate and Energy Program (GCEP), an industrially sponsored renewable energy program, coordinated by Stanford University.

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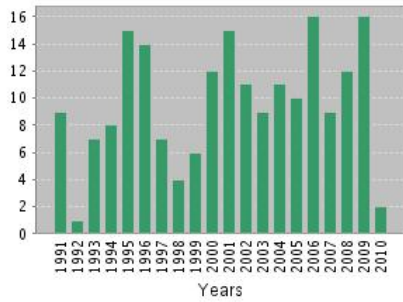
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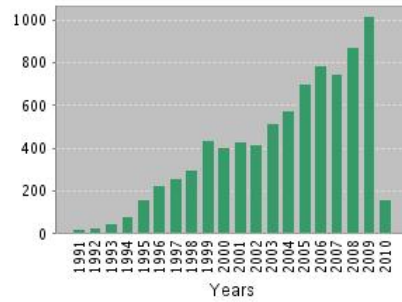
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