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Trends in plasma-enhanced atomic layer deposition

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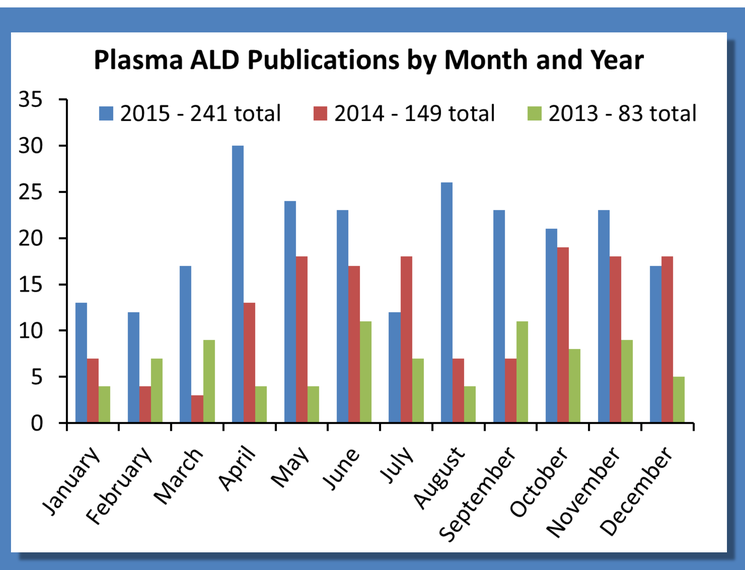
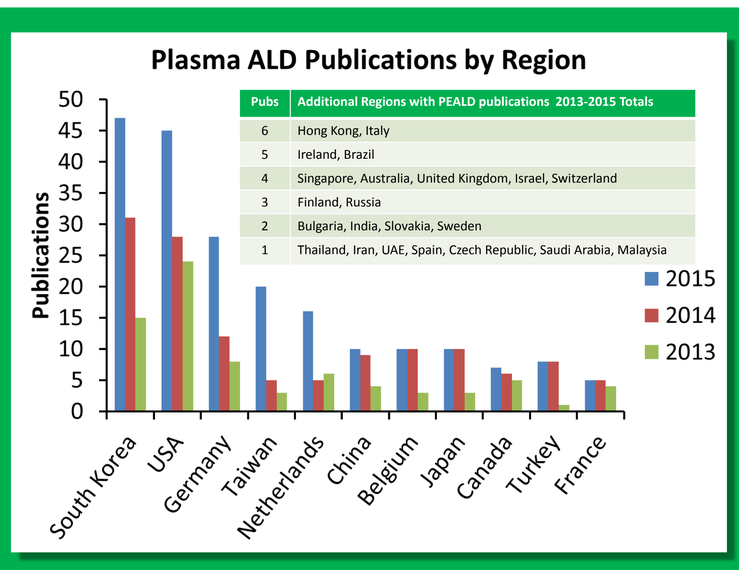
- Plasma-enhanced atomic layer deposition (PEALD) has made rapid gains in popularity in recent years due to the superiority of PEALD films vs. films from thermal ALD and other deposition technologies for certain materials and applications. Much of the growth is due to researchers outside of the ALD community integrating the new technology into their own work.
- To better understand the trends of this increasingly popular deposition technique, we have developed a database of publications, conference proceedings, etc. in which PEALD films have been used. In the database, we catalog these items by film composition, hardware, precursors, authors, affiliations, region, journal, date, film properties and analysis techniques, substrates, etc..
- Below are interesting plots highlighting the trends in PEALD from data made possible by the free, on-line database at www.plasma-ald.com

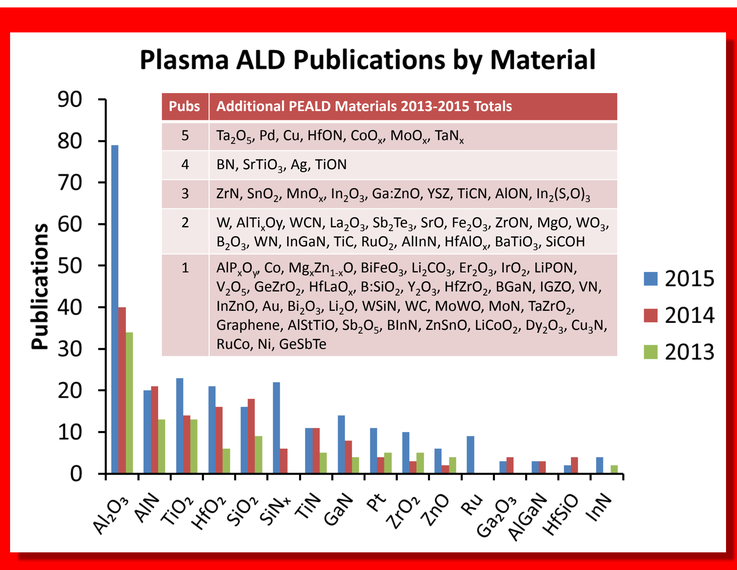


- We have identified 473 PEALD publications from 2013 – 2015
- 2013 – 83 publications
- 2014 – 80% growth to 149 publications
- 2015 – 62% growth to 241 publications
- 2016 – 63 publications found for the first 4 months so far



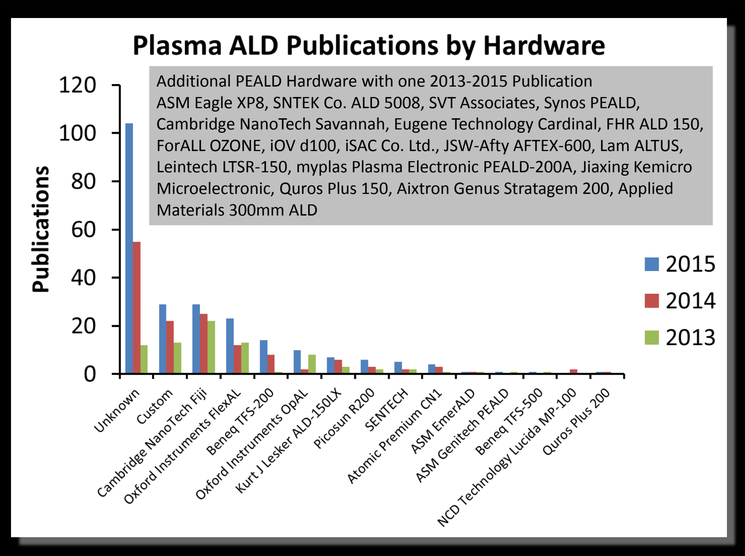
Pubs	Additional Regions with PEALD publications 2013-2015 Totals
6	Hong Kong, Italy
5	Ireland, Brazil
4	Singapore, Australia, United Kingdom, Israel, Switzerland
3	Finland, Russia
2	Bulgaria, India, Slovakia, Sweden
1	Thailand, Iran, UAE, Spain, Czech Republic, Saudi Arabia, Malaysia

- PEALD publications are coming from all over the world
- Each of the 11 regions in the plot above had at least 14 PEALD publications 2013 – 2015
- 22 additional regions contributed 1 to 6 PEALD publications and are listed in the inset table
- USA led in 2013 but South Korea has had the most the past two years with Germany a consistent third



Pubs	Additional PEALD Materials 2013-2015 Totals
5	Ta_2O_5, Pd, Cu, HfON, CoO_x, MoO_x, TaN_x
4	BN, $SrTiO_3$, Ag, TiON
3	ZrN, SnO_2, MnO_x, In_2O_3, Ga:ZnO, YSZ, TiCN, AlON, $In_2(S,O)_3$
2	W, $AlTi_xOy$, WCN, La_2O_3, Sb_2Te_3, SrO, Fe_2O_3, ZrON, MgO, WO_3, B_2O_3, WN, InGaN, TiC, RuO_2, AlInN, $HfAlO_x$, $BaTiO_3$, SiCOH
1	AlP_xO_y, Co, $Mg_xZn_{1-x}O$, $BiFeO_3$, Li_2CO_3, Er_2O_3, IrO_2, LiPON, V_2O_5, $GeZrO_2$, $HfLaO_x$, $B:SiO_2$, Y_2O_3, $HfZrO_2$, BGaN, IGZO, VN, InZnO, Au, Bi_2O_3, Li_2O, WSiN, WC, MoWO, MoN, $TaZrO_2$, Graphene, AlStTiO, Sb_2O_5, BInN, ZnSnO, $LiCoO_2$, Dy_2O_3, Cu_3N, RuCo, Ni, GeSbTe

- Al_2O_3 is by far the most popular PEALD film showing up in 27-41% of each year's publications
- The plot above shows the annual frequency of the top 16 films that have been described in at least 6 publications during 2013-2015
- 76 additional PEALD materials have been discussed during these years and are listed in the inset table
- The full database has information on over 130 PEALD materials



- We have identified 30 different commercial PEALD systems in the 2013 – 2015 publications and many custom systems exist as well.
- The plot to the left identifies the top 13 commercial systems by number of publications. The remaining 17 commercial systems are listed in the inset text box.
- It is difficult to determine the most popular systems because each year, a larger proportion of the publications do not identify the hardware used. We believe this is due to the PEALD films being used in many new applications where PEALD is not the focus of the research and the authors do not find it necessary to give the deposition details. The acceptance of PEALD into other fields should be very exciting for our community.

- Over 1650 authors are represented in these publications
- The table below lists the top 31 authors with the most PEALD publications and the number of authors with fewer papers.

2013-2015 PEALD Publications	Top 31 PEALD Publication Authors 2013-2015
24	Erwin Kessels
17	Necmi Biyikli
16	Çagla Özgit-Akgun
12	Ali Kemal Okyay, Ken Cadien
11	Kensaku Kanomata
10	Miin-Jang Chen
8	P. Pungboon Pansila, Pouyan Motamedi, Shigeru Kubota, Bashir Ahmmad, Fumihiko Hirose, Christophe Detavernier
7	Olivier Poncelet, Neeraj Nepal, Jhih-Jie Huang, Eda Goldenberg, Ali Haider, Harm C. M. Knoops, Charles R. Eddy, Jr.
6	Laurent A. Francis, Kyle Bothe, Marcel A. Verheijen, Hassan Gargouri, Hyeongtag Jeon, Douglas Barlage, Ageeth A. Bol, Min-Hung Lee, Jihwan An, Jolien Dendooven, Kyle Bothe
9 – 5 pubs, 37 – 4 pubs, 93 – 3 pubs, 279 – 2 pubs, and 1209 – 1 pub	

- 115 different chemicals were used in these publications
- Unsurprisingly, trimethylaluminum (TMA) and oxygen plasma are the two main chemistries in use
- Looking at how many precursors have been tried for a specific element points to challenging materials
  - Si had 16 precursors
  - Ti had 9 precursors
  - Ru had 7 precursors
  - W had 5 precursors
  - Cu, In, Ta each had 4 precursors
  - B, Co, Ga, Hf, Sn, Zr each had 3 precursors
- For other materials, a single precursor has been decided
  - 17 Pt papers all with $MeCpMe_3Pt$
  - 12 ZnO papers all with $ZnEt_2$
  - All but 3 of the 153 occurrences of Al_2O_3 used TMA
- O_2, N_2, H_2, NH_3, and Ar are the main plasma gases but interesting discoveries have been made with D_2, CH_4, N_2O, CO_2, H_2O, and H_2S plasmas as well

Plasma-enhanced atomic layer deposition is an exciting, growing field that is becoming more recognized as an indispensable tool to researchers outside the ALD community. The free, on-line database at www.plasma-ald.com can help you quickly find PEALD publications that will help you with your research interests.

If you have any questions or comments, please send me an email: plasma-ald-guy@plasma-ald.com