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14. ABSTRACT The goal of the project was to take an interdisciplinary approach to the improvement of high temperature devices, with an emphasis on the fabrication and optimization of metal-semiconductor connections, junction field effect transistors and other heterojunction structures. We have focused on boron carbide and silicon carbide substrate materials and have made progress in the improvement of direct-write fabrication processes for the formation of metal connections and other heterojunctions. Accomplishments made in the boron carbide involve the development of protocols for fabrication of substrates and for doping with phosphorous and nickel. For silicion carbide CVD, we have demonstrated that carbonyl-containing organics lead to SiC formation, but have not been able to extend the material's growth past the sub-monolayer level at the time of this report. A major success has been the discovery of polymers, based on the vinylidene monomer, that can be directly photo-etched in a process useful to film resist lithography. Finally the metallocenes have been developed for CVD for a number of metals, eg., Fe, Ni, Co, Ru, under a variety of conditions. The metallocene-like Pd(η^5 -C ₅ H ₅) (η^3 -C ₃ H ₅) has been shown to be a very effective source compound for the low temperature deposition of palladium.					
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I. INTRODUCTION

This final technical report summarizes progress made in AFOSR grant # F49620-98-1-0463, entitled "High Temperature/High Speed Junction Devices and Contacts". The grant provided \$306,014 in funding from AFOSR matched by \$247,574 in state and industrial cost share over the period 5/15/98 to 5/14/01 and involved collaborative efforts in physics, chemistry and engineering disciplines. In addition to the four co-investigators (Profs. Peter Dowben, Natale Ianno, Marjorie Langell and Brian Robertson), one postdoctoral researcher, nine graduate students and four undergraduate students were associated with the project, resulting in 21 publications, two patents awarded, three patents submitted, 13 presentations and five graduate-level theses.

The goal of the project, as described in the original research proposal, was to take an interdisciplinary approach to the improvement of high temperature devices, with an emphasis on the fabrication and optimization of metal-semiconductor connections, junction field effect transistors and other heterojunction structures. The proposed work has spanned the range of device research, from development of novel substrates and fabrication methods, direct-writing of nanoscaled metal deposition, heterojunction and metal connect fabrication and testing, to the actual construction and characterization of prototype electronic devices. Because we are interested in devices that operate under extreme conditions, we have focused on the use of boron carbide and silicon carbide substrate materials. We have also made progress in the improvement of direct-write fabrication processes for the formation of metal connections and other heterojunctions. Finally, we have continued our work in the fabrication, testing and optimization of working prototype junction field effect transistors (JFETS) and metal-semiconductor field effect transistors (MESFETS) using the high temperature, high performance substrates and CVD direct-write nanostructured metal connects developed in previous phases of the research.

II. SUBSTRATE MATERIALS

Advances in electronic devices are made along a number of directions, including identification of new substrate materials, optimization of substrate fabrication methods, improved doping, device design, contact formation and device miniaturization. Progress described in this section focuses on the first two areas. We have previously developed a class of novel molecular precursors, based on their icosahedral structure which mimics that of crystalline boron carbide. We had also developed protocols for CVD methods for fabrication of boron carbide substrates and doping of these materials with phosphorous and nickel. Accomplishments made under AFOSR grant #F49620-98-1-0463 in the boron carbide area build on past successes and tie up many loose ends in our boron carbide activities.

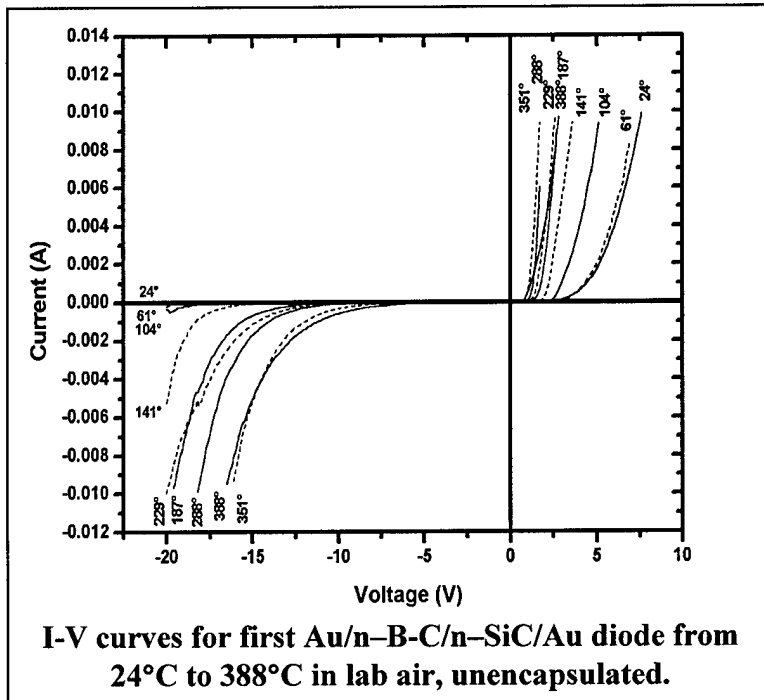
In agreement with our previous x-ray diffraction measurements, we were able to perform electron diffraction and imaging in a transmission electron microscope to demonstrate unequivocally that PECVD boron-carbide deposited from the molecular precursor o-carborane is nanocrystalline and that the volume fraction of the as-grown material contained in the nanocrystallites can be as high as 50%. This refutes the possibility that PECVD boron-carbide material is in fact largely amorphous and demonstrates that the material is suitable for many device application as it stands. Our TEM data obtained from PECVD films from stripped Si

substrates show clearly that the material can be completely converted to crystalline form by bombardment with high energy ($\sim 5\text{keV}$) Ar^+ . The crystallite sizes deduced from the width of the electron diffraction peaks range from 12 to 200 nm. In these substrates, there are at least two boron carbide polytypes, both of which are fully crystalline. The TEM data, therefore, confirm the importance of PECVD process control in the project and justify our work towards identifying the best polytypes for electronic use of PECVD boron carbide.

In a parallel synthesis project, we have succeeded in rf magnetron sputter deposition of high-resistivity boron carbide substrates. This was accomplished by saturating a boron carbide target in a methane plasma and depositing the boron carbide from the target. The optical band gap of substrates obtained in this manner is consistently smaller than that of PECVD films of the same composition. The electrical resistivity of the sputter-deposited B_5C films (approximate composition) is also smaller than comparable PECVD deposited films, which in part is most likely a direct result of the smaller band gap. Nevertheless, these films were obtained with record-high resistivities for sputter-deposited materials, approximately 10^7 ohm-cm. The main peaks found in x-ray diffraction scans of sputter-deposited films agree in position with those obtained from PECVD-deposited materials and indicate similar microstructure. Infrared absorption measurements show that the PECVD films contain more hydrogen than the sputtered films. Furthermore, the hydrogen in the PECVD films is bound directly to carbon in the form of methyl groups, with the exception of a small amount bound in terminal linkage to boron. Hydrogen in the PECVD-deposited films may serve to terminate dangling bonds, accounting for increased electrical resistivity and a larger band gap with respect to sputtered films of the same composition, as has been observed in a-SiH substrates.

During the course of this grant, we have fabricated the first reported PECVD B-C/SiC devices and have characterized their device properties. Operation of these n-B-C / n-SiC diodes

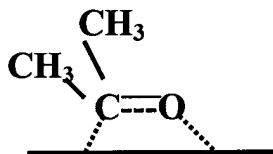
was performed from 24 to 388°C , with the temperature range limited primarily by the capabilities of our measurement equipment. The I-V data displayed here are for an unencapsulated device in laboratory air; the lack of packaging likely relates to the deviation in behavior at the highest temperatures. Ideality factors, decreasing from ~ 20 to under 2 with increasing temperature, are comparable with those for diodes based on microcrystalline Si. The linearity of the relation between the derived series resistance and inverse temperature gives a characteristic energy barrier for holes of 0.11 eV, compared with 0.35 eV for B-C grown on n-Si.



We have also created working heterojunctions between sputter-deposited B₅C, and n-Si(111), n-Si(100), p-Si(100) and p-Si(111) in order to demonstrate the compatibility of the rf sputter fabrication process with present silicon substrate technology and to obtain an estimate of the potential quality of the heterojunctions produced. In this part of the research, PECVD B₅C/n-Si junctions were also fabricated and were shown to exhibit characteristics similar to those of the B₅C/n-Si rf sputtered substrates. Publications documenting device characteristics are listed below.

Under present grant funding, we have built upon our past success with boron carbide to include the development of a fabrication process for silicon carbide, whose use is presently limited by the high cost resulting from the lack of a rapid and general synthetic protocol. The research, as initially proposed, sought a chemical vapor deposition method for SiC, thus alleviating the major impediment for its use in the semiconductor industry. We have demonstrated that carbonyl-containing organics do lead to SiC formation, but have not been able to extend the material's growth past the sub-monolayer level at the time of this report. We have focused on the use of acetone (CH₃COCH₃), one of the simplest organic carbonyls, because it is cheap, relatively nontoxic and easy to handle in an industrial setting. Both thermal and electron catalyzed decomposition of acetone are possible on Si(100) surfaces, which otherwise are found to be uncontaminated when the substrate is flashed briefly to 600- 700°C after exposure of the Si(100)-acetone adsorbate complex to electron flux.

The initial, and most important, adsorbate interaction appears to be in the rehybridization of the $\pi_{C=O}$ functionality:



which firmly attaches the organic moiety to the surface. The C-C and C-H bonds then become more easily broken, with C-H bonds sensitive to photon or electron assisted decomposition and C-C bonds more thermally labile. Thus, some amount of control over rates and mechanisms of decomposition is possible. Although a series of intermediate adsorbate complexes have been identified by high resolution electron energy loss spectroscopy (HREELS), the final surface product upon annealing the Si(100)-(CH₃)₂CO surface is SiC. The substrate remains otherwise uncontaminated.

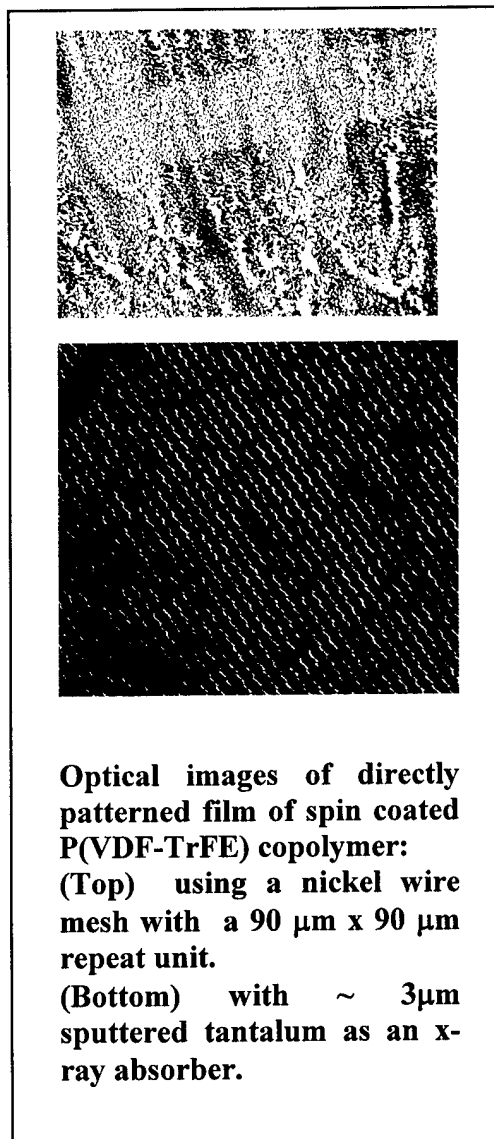
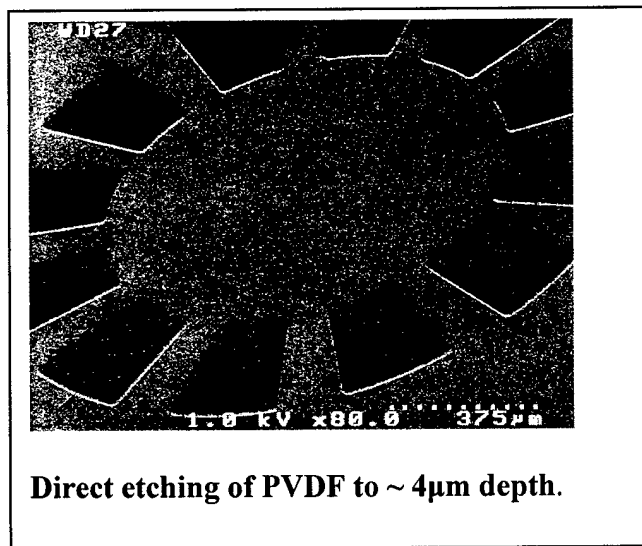
To extend this process beyond the monolayer level, a source of silicon must be included in the CVD mixture. Unfortunately, we have yet to identify a CVD precursor mixture that allows uncontaminated, crystalline growth of multilayer SiC. Work on this project continues at the time of the grant report.

III. CONTACTS, WIRE INTERCONNECTS AND NANOSTRUCTURES

(Expenses for this part of the project have been shared with University of Nebraska-Lincoln Center for Materials Research and Analysis and with the Nebraska Research Initiative program "Nanoscale Materials for Information Technologies".)

A major success of this research program has been the discovery that a class of unique, thin-film polymers based on the vinylidene monomer unit, polyvinylidene fluoride PVDF and its co-polymer polyvinylidene fluoride-trifluoroethylene P(VDF-TrFE) can be directly photo-etched using synchrotron-based x-rays to yield microstructures in a process that is potentially useful to film resist lithography.

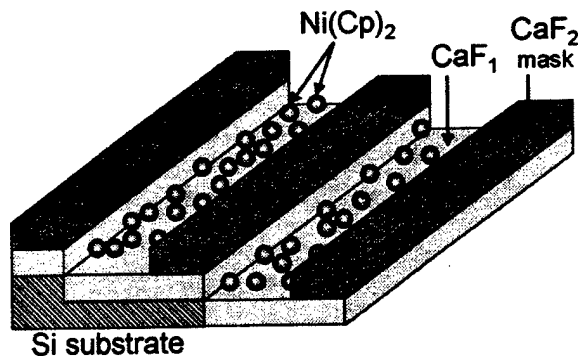
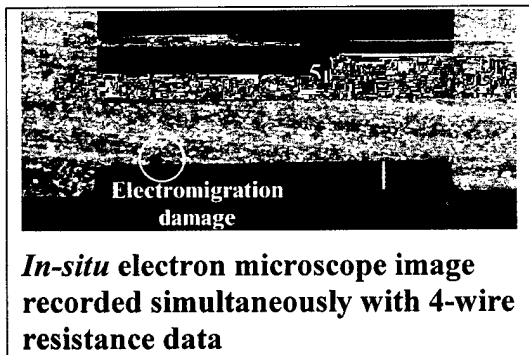
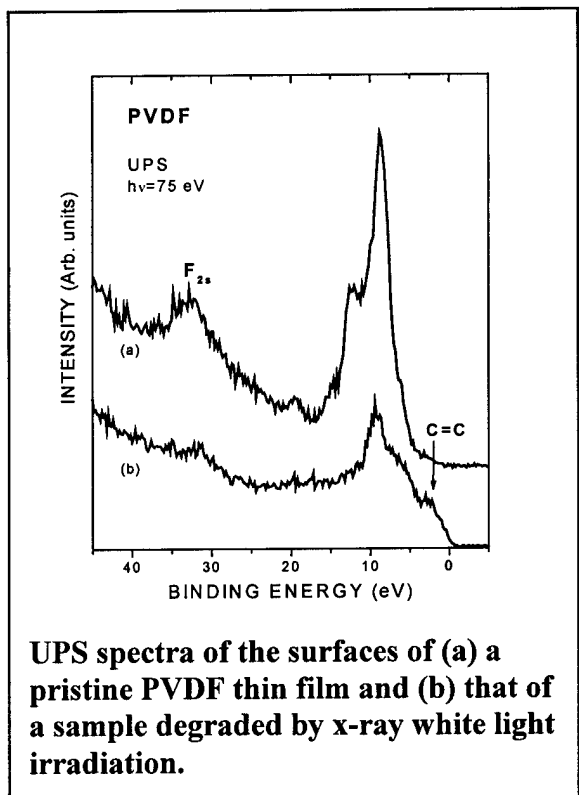
As examples, figures to the right and directly below this paragraph show PVDF microstructures, which have been directly patterned upon exposure of spin-cast polymers to synchrotron broad band x-ray radiation. The structures have been formed in a single step, without any need of post-processing or additional development. This synchrotron patterning study has allowed us to demonstrate that PVDF and P(VDF-TrFE) films, which possess unique and technologically important material properties, can be directly patterned by standard x-ray lithographic processes in a manner that makes their use versatile and widely applicable to present device fabrication practices. We have demonstrated this capability and have developed the process sufficiently to allow direct pattern transfer technology as a new type of novel x-ray resist masks. One US Patent has already been submitted documenting this technique.



In order to optimize the direct-patterning process, ultraviolet photoemission spectroscopy (UPS) and mass spectrometric methods were used to elucidate the photodegradation mechanism of (PVDF) and P(VDF-TrFE) co-polymer thin films under x-ray flux. Upon increased fluence to x-rays with $h\nu = 1000$ eV, UPS measurements revealed that substantial chemical modifications occurred for both 100 Å PVDF and 5 monolayer (~ 15 Å) P(VDF-TrFE) films. Changes observed include the emergence of new valence band features near the Fermi level, indicating a

semi-metallic photodegradation product. These changes are demonstrated in UP spectra shown to the right. In the mass spectrometric analysis of the degradation products, photodetached fragments of both PVDF and of the copolymer P(VDF-TrFE) were elucidated. These species consist mainly of H_2 , HF, CHF and CH_2 .

In our study of processes and kinetics relevant to high-temperature device operation, we have identified a potentially important path to efficient, comprehensive methods for limiting electromigration in contacts and interconnects. In our smallest wires, current flow is greatly suppressed by the restricted dimensions, and electromigration tends to dominate. To this effect, we have conducted proof-of-principle studies with a scanning transmission electron microscope (STEM) for *in situ* observation and quantitative characterization during electromigration testing of contacts and interconnects. The STEM system that we developed during the course of this grant is ideally suited to the study of electromigration. We have demonstrated that a spatial resolution of 5 nm is maintained during annealing of a sputtered aluminum layer, which we used as a test substitute for a contact pad or interconnect. The STEM has now also been modified with the requisite 4- and 6-wire connections for making high-precision resistance measurements simultaneously with observing changes in the metallurgical microstructure in contacts and interconnects.

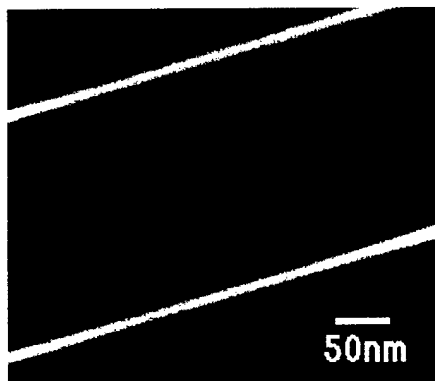


IV. CVD Processes and Novel CVD Materials

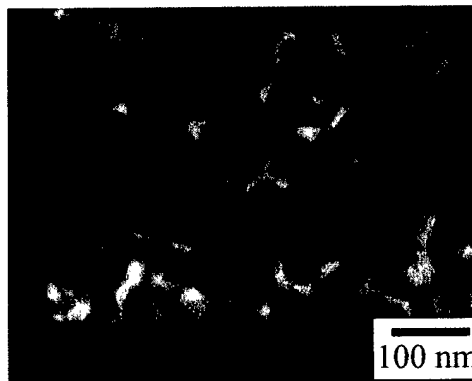
(Expenses for this part of the project have been shared with University of Nebraska-Lincoln Center for Materials Research and Analysis and with the Petroleum Research Foundation.)

To be optimally useful, CVD materials must deposit their metals cleanly. For selective area deposition, there is the added restriction that the CVD molecule must only deposit metals in

areas under active electron or photon beam stimulation. We have developed a novel class of CVD precursor molecules, the metallocenes, for selective-area metal deposition and have elucidated their adsorption, desorption and decomposition mechanisms on a wide range of substrates. These organometallics can be deposited sufficiently cleanly that we have been able to use them successfully for everything from nanoscale wire deposition to dopant of wide band gap semiconductor substrates. These latter substrates have been incorporated into working prototype devices. Examples of electron-beam induced CVD of nano-scaled nickel wires and three dimensional structures are shown below.



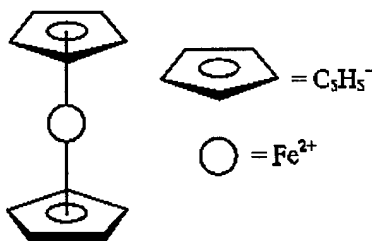
(a)



(b)

Selective area deposited nanopatterned materials – electron beam induced fabrication of (a) 8nm Ni wires and (b) 3-D nanostructures.

Ferrocene, $\text{Fe}(\text{C}_5\text{H}_5)_2$, is the prototypical metallocene and its properties foretell the superior characteristics of this class of material for photon and electron activated CVD deposition. $\text{Fe}(\text{C}_5\text{H}_5)_2$ decomposes readily under electron or photon irradiation and therefore can be used as selectively-activated CVD source molecules for the formation of thin metal films on a variety of substrates.

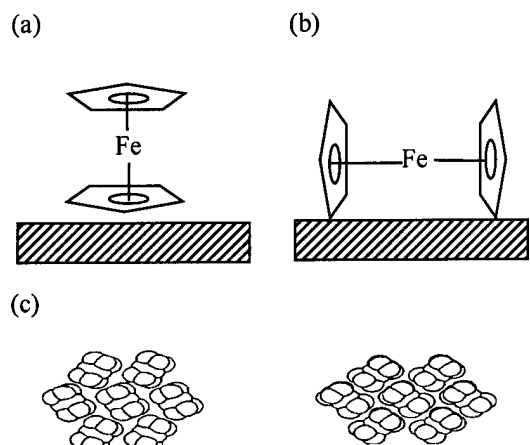


Ferrocene, $\text{Fe}(\text{C}_5\text{H}_5)_2$ the prototype metallocene.

Ferrocene's properties can be contrasted with another CVD source molecule for iron deposition, $\text{Fe}(\text{CO})_5$, which has been extensively investigated for this purpose. While $\text{Fe}(\text{CO})_5$ is a highly toxic liquid, ferrocene is a less toxic solid with extraordinary thermal stability to greater than 773 K, yet it possesses sufficiently high vapor pressure, 0.966 Pa at 298 K, to make it amenable to CVD processes. Therefore the metallocene has better materials-handling properties for CVD

applications. It is also possible to substitute the cyclopentadienyl $\{\text{C}_5\text{H}_5^-\}$ ligands of the metallocene with other organic functions to change stability, volatility, and adsorption properties to make it deposit more cleanly and with greater spatial control.

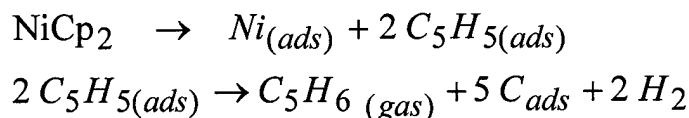
Metallocenes do make excellent CVD precursor molecules for deposition of a number of metals, *eg.*, Fe, Ni, Co, Ru, under a variety of conditions. However, there are caveats to their usage. We have recently developed a very detailed picture of the thermal decomposition of nickelocene and have shown that, even under the best of circumstances, some decomposition of the metallocene occurs even in the absence of irradiation. This has led to the proposal of new, substituted metallocene CVD precursor molecules with greater chemical stability and to proposed changes in CVD protocol. For example, a high nickelocene flux in the presence of hydrogen may improve the cleanliness of the deposition procedure for nickel metal. It also may be possible to scavenge improperly deposited metal by judicious exposure to cyclopentadiene, the metallocene volatilizing ligand. We are presently testing these proposals for efficacy at the laboratory scale.



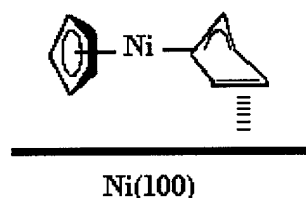
Surface orientations of molecularly adsorbed ferrocene for the molecular axis a) along the surface normal and b) parallel to the surface plane. Bulk ferrocene has the two common crystal structures shown in c.

For the most reactive metallocene/substrate combinations, the metallocene decomposes uncontrollably without irradiation, destroying the clean and selective nature of the CVD photocatalyzed process. We have shown that reactive mechanisms involve a tilting (see left figure) or side-way adsorption of the molecule either just prior to or during thermal decomposition. We postulate that if we can prevent the molecule from adsorbing with its molecular axis with substantial tilting, we might be able to stabilize it to thermal decomposition and, thus, improve its performance as a CVD source molecule. This has led us to propose a new ligand, the hexamethylated cyclopentadienyl group, as an improved ligand for CVD source molecule applications.

The choice of substrate and adsorption conditions has been found to influence the chemistry of the adsorbed metallocene. For example, the primary mechanism of thermal decomposition of nickelocene, $\text{Ni}(\text{C}_5\text{H}_5)_2$, on $\text{Ag}(100)$ occurs through loss of its cyclopentadienyl ligands followed by disproportionation of the adsorbed upon the silver surface:



The same metallocene on a $\text{Ni}(100)$ substrate leads to hydrogenation:

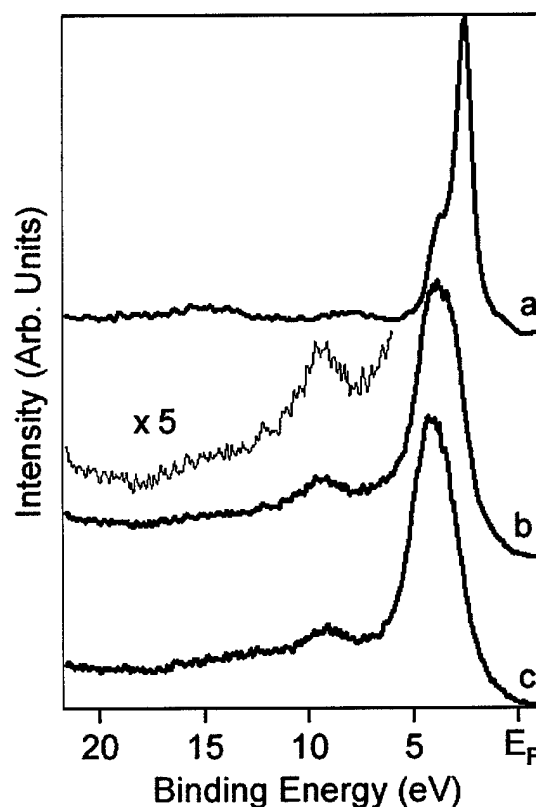


and ultimate decomposition into propylene and acetylene in a mechanism reminiscent of a reverse cyclo-oligomerization. The initial source for hydrogenation may be either ambient hydrogen, which is difficult to eliminate under typical CVD reaction conditions, or a small amount of dissociated metallocene.

In studies of metallocene-like molecules and metallocene derivatives we have studied the photolytic decomposition of the volatile palladium organometallic species allylcyclopentadienyl palladium, $\text{Pd}(\eta^5\text{-C}_5\text{H}_5)(\eta^3\text{-C}_3\text{H}_5)$. Our results are consistent with deposition studies showing that $\text{Pd}(\eta^5\text{-C}_5\text{H}_5)(\eta^3\text{-C}_3\text{H}_5)$ is a very effective source compound for the low temperature photolytic deposition of palladium. We further have demonstrated that $\text{Pd}(\eta^5\text{-C}_5\text{H}_5)(\eta^3\text{-C}_3\text{H}_5)$ can be used to make Pd-Cu alloyed surfaces on Cu(111).

CVD with this molecular precursor has now been developed to the point that it is an established procedure in our group for the selective-area laser-assisted chemical vapour deposition of palladium as thin films and multilayers. Prior to our recent publications, no direct study of the surface adsorption of $\text{Pd}(\eta^5\text{-C}_5\text{H}_5)(\eta^3\text{-C}_3\text{H}_5)$ had ever been reported, in spite of the fact that a molecular precursor state is part of the postulated mechanisms for photolytic decomposition in the near UV of allylcyclopentadienyl palladium, $\text{Pd}(\eta^5\text{-C}_5\text{H}_5)(\eta^3\text{-C}_3\text{H}_5)$. Such a precursor state requires the presence of adsorbed molecules or molecular fragments on the surface. The typical energy of the radiation for photolysis (3.67 eV, 337 nm) is insufficient to cause complete decomposition to palladium metal, as we have shown through consideration of the thermodynamic cycles of the energetics of decomposition.

Photoemission spectra taken at normal emission and a 45° light incidence angle (s+p-polarization) from a) clean Cu(111), b) 780 L exposure of $\text{Pd}(\eta^5\text{-C}_5\text{H}_5)(\eta^3\text{-C}_3\text{H}_5)$ to Cu(111) at 160 K, and c) following an annealing treatment at 330 K. The photon energy is 50 eV. The Fermi level (zero binding energy) is established from the clean metal surface.



We have elucidated the energetics of this procedure and have identified key intermediates in the process. Photoemission spectra of the Cu(111) surface following exposure to $\text{Pd}(\eta^5\text{-C}_5\text{H}_5)(\eta^3\text{-C}_3\text{H}_5)$, shown on the previous page, exhibit new weak bands at 9 eV and 15 eV binding energy upon annealing of the copper-metallocene complex while the Cu 3d bands become part of a broader photoemission feature extending from 3.5 to 5 eV binding energy (curve b, previous page). The increase in the Cu 3d bands feature width is characteristic of a Cu-Pd alloy surface. It is clear that most, and indeed almost all, of the $\text{Pd}(\eta^5\text{-C}_5\text{H}_5)(\eta^3\text{-C}_3\text{H}_5)$ has decomposed leaving deposited Pd atoms on the surface.

Because of the strong tendency for copper to segregate to the surface of Cu-Pd alloys, the surface forms a surface alloy that has a distinctive hybrid d-band electronic structure characteristic of neither copper nor palladium; the Cu-Pd bimetallic alloy also exhibits surface reactivity that does not resemble that of either constituent metal. Thus, this CVD precursor molecule shows potential in materials applications well beyond that initially envisioned for it as a simple source of palladium metal deposition.

V. PERSONNEL

There are currently established partnerships within the group involving several national laboratories: the Center for Advanced Microstructure and Devices (CAMD) in Baton Rouge-Louisiana and the National Synchrotron Light Source (NSLS) at Brookhaven for access to synchrotron radiation, and Oak Ridge National Laboratory for access to neutrons. At the international level, there are ongoing links within the group to the University of Salford (UK), where our collaborator Dr. Neil Boag is Senior Lecturer. We have exchanged students at the undergraduate and graduate levels between Salford and UNL over the past several years, a number of whom have been funded by or otherwise involved in this grant. Partnerships are also in place between UNL and both Grambling State and Alcorn State Universities involving exchange of both students and faculty between our respective science departments.

The current AFOSR contract has substantially contributed to the education of:

Undergraduates:

Ms. Veronica Holmes (Department of Chemistry, Southern University)
Mr. Seth Root (Department of Physics, University of Nebraska)
Ms. Jocelyn Bosely (Department of Physics, University of Nebraska)
Ms. Ellen Day (Department of Physics, Salford University)

Graduate students:

Mr. Mengjun Bai (predoctoral, Physics)
Dr. Camilia Borca (Degree awarded May 2001, Physics)
Mr. Rui-Hua Cheng (predoctoral, Physics)
Dr. Ismail Gobulukoglu (Degree awarded December 2000, Mechanical Engineering)
Mr. Andrew Harken (master's candidate, Mechanical Engineering)
Dr. Hong Jiang (Degree awarded December 2000, Mechanical Engineering)

Dr. David Pugmire (Degree awarded May 2000, Chemistry)

Ms. Laurence Sage (Master's from University of Franche-Comte-Besancon, awarded 1999, Chemistry)

Ms. Cynthia Woodbridge (predoctoral, Chemistry)

The senior personnel working on this project was a post-doc: Dr. Jaewu Choi, who has just been offered a tenure track faculty position at Wayne State University.

VI. PUBLICATIONS

Published:

1. D.L. Pugmire, C.M. Woodbridge and M.A. Langell, "Orientation of Nickelocene on Ag(100)", *Surface Sci.*, **411** (1998) L844.
2. C.W. Hutchings, A.P. Hitchcock, A.T. Wen, S.-D. Hwang, J.A. Glass, J.T. Spencer, Y.-F. Hu, G.M. Bancroft, and P.A. Dowben, "The Valence Band Photoemission and Near Edge Core Excitation Spectroscopy of Di-t-butylchlorophosphine", *J. Electron. Spectrosc. Rel. Phenom.*, **94** (1998)187-194.
3. B.W. Robertson and P.A. Dowben "Boron-Carbon Alloy Development for Use in High Temperature Devices and Sensors", *Proceedings of the Second European Conference on High Temperature Electronics*, Manchester, England, 1997 (published in 1998) 219.
4. Seong-Don Hwang, S.S. Kher, J.T. Spencer, S. Datta and P.A. Dowben, "Laser Induced Selective Copper Deposition on Polyimides and Semiconductors from Solution", *Metallized Plastics 4: Fundamentals and Applications*, Edited by K.L. Mittal (1998) 9.
5. C.W. Hutchings, S.-D. Hwang, P.A. Dowben, J.A. Glass, J.T. Spencer, Y.-F. Hu and G.M. Bancroft, "The Electronic Structure of Di-t-butylchlorophosphine", *Phys. Low Dim. Struct.* **1/2** (1998) 65-70.
6. Ahmad A. Amad, N.J. Ianno, Seong-Don Hwang and P.A. Dowben, "Sputter Deposition of High Resistivity Boron Carbide", *Thin Solid Films* **335** (1998) 174-177.
7. D.N. McIlroy, S.-D. Hwang, K. Yang, N. Remmes, P.A. Dowben, Ahmad A. Ahmad, N.J. Ianno, J.Z. Li, J.Y. Lin, and H.X. Jiang, "The Incorporation of Nickel and Phosphorus Dopants into Boron Carbon Alloy Thin Films", *Applied Physics A67* (1998) 335-342.
8. D.L. Pugmire, C.M. Woodbridge, S. Root and M.A. Langell, "Nickelocene Adsorption on Single-Crystal Surfaces", *J. Vac. Sci. Technol.*, **17** (1999) 1581
9. J.-L. Lin, H. Rauscher, A. Kirakosian, F.J. Himpsel, and P.A. Dowben, "Selective Adsorption of Metallocenes on Clean and Chemically Modified Si(111) Surface", *J. Applied Physics* **86** (1999) 5492-5496.
10. I. Gobulukoglu and B.W. Robertson, "In Situ STEM Technique for Characterization of Nanoscale Interconnects during Electromigration Testing", in "Materials Reliability in Microelectronics IX", MRS Proceedings, Vol. 563, (1999) 181-6
11. Harish M. Manohara, Eizi Morikawa, Jaewu Choi and Phillip T. Sprunger, "Pattern Transfer by Direct Photo Etching of Poly(vinylidene fluoride) using X-rays", *IEEE Journal of Microelectromechanical Systems* **8** (1999) 417-423.
12. Jaewu Choi, H.M. Manohara, E. Morikawa, P.T. Sprunger, P.A. Dowben, and S.P. Palto, "Thin Crystalline Functional Group Copolymer(vinylidene fluoride - trifluoroethylene) Film Patterning Using Synchrotron Radiation", *Appl. Physics Letters* **76** (2000) 381-383.

13. C.M. Woodbridge, D.L. Pugmire, R.C. Johnson, N.M. Boag and M.A. Langell, "HREELS and XPS Studies of Ferrocene on Ag(100)" *J. Phys. Chem. B*, **104(14)** (2000), 3085-3093.
14. Eizi Morikawa, Jaewu Choi, Harish M. Manohara, Hisao Ishii, Kazuhiko Seki, Koji K. Okudaira and Nobuo Ueno, "Photoemission study of direct photo-micromachining in poly(vinylidene fluoride)", *Journal of Applied Physics*, **87** (2000) 4010-4016.
15. J.-L. Lin, D.Y. Petrovykh, A. Kirakosian, H. Raucher, F.J. Himpsel, and P.A. Dowben, "Self Assembled Fe nanowires using organometallic chemical vapor deposition and CaF₂ masks on stepped Si(111)", *Applied Physics Letters* **78** (2001) 829-831.
16. D.L. Pugmire, C.M. Woodbridge, N.M. Boag and M.A. Langell, "Adsorption and Decomposition of Nickelocene on Ag(100): A HREELS and TPD Study", *Surface. Sci.*, **420** (2001) 155-171.
17. J.L. Lin, D.Y. Petrovykh, A. Kirakosian, H. Rauscher, F.J. Himpsel and P.A. Dowben, "Self-assembled Fe nanowires using organometallic chemical vapor deposition and CaF₂ masks on stepped Si(111)", *Appl. Phys. Letters*, **78** (2001), 829-831.

In press or submitted :

18. Jaewu Choi, Neil M. Boag and Peter A. Dowben, "The Adsorption and Decomposition of Pd(η^5 -C₅H₅)(η^3 -C₃H₅) on Cu(111)", submitted to Chem. Comm.
19. M. Bai, S. Adenwalla and B.W. Robertson, "Crystallites in Boron-Carbon Alloys Grown by Plasma Enhanced Chemical Vapor Deposition", submitted to *Appl. Phys. Lett.*
20. H. Jiang, C.N. Borca, Bo Xu, and B.W. Robertson, "Fabrication of 2- and 3-Dimensional Nanostructures", *International Journal of Modern Physics B*, submitted.
21. S. Adenwalla, P. Welsch, A. Harken, J.I. Brand, A. Sezer and B.W. Robertson, "Characterization of PECVD Boron-Carbide Materials and B-C/SiC Diodes", in Proceeding of the 5th High Temperature Electronics Conference (HiTEC), Albuquerque, June 2000, in press.

VII. PRESENTATIONS

1. "Characterization of Nanoscale Interconnects by In Situ STEM Analysis during Electromigration Testing", I. Gobulukoglu and B.W. Robertson, MRS 1999 Spring Meeting, San Francisco, April 1999.
2. "Boron-Carbon Semiconductor High-Temperature Devices and Sensors", B.W. Robertson, S. Adenwalla, M. Bai, E. Day and P.A. Dowben, 1999 NASA / JPL Conference on Electronics for Extreme Environments, Pasadena, California, February 1999.
3. M. Bai, B.W. Robertson, S. Adenwalla, and C. Davenport, "Characterization of PECVD Boron-Carbide Alloys and Devices", 109th Annual Meeting of the Nebraska Academy of Sciences, April 1999.
4. I. Gobulukoglu and B.W. Robertson, "In Situ STEM Characterization of Nanoscale Interconnects", in 109th Annual Meeting of the Nebraska Academy of Sciences, April 1999.
5. H. Jiang and B.W. Robertson, "Electron Beam-Induced Organometallic CVD of Magnetic Nanostructures: Fabrication and Characterization", in 109th Annual Meeting of the Nebraska Academy of Sciences, April 1999.

6. D.L. Pugmire, C.M. Woodbridge, S. Root and M.A. Langell, "Nickelocene Adsorption on Single Crystal Surfaces", in 45th International Meeting of the American Vacuum Society, Baltimore, MD, Nov. 2, 1998.
7. D.L. Pugmire, C.M. Woodbridge and M.A. Langell, "Nickelocene Adsorption and Desorption from the Ag(100) Surface" in Rocky Mountain regional meeting of the AVS, Arvada, CO, August 19, 1999.
8. C.M. Woodbridge, X.J. Gu and M.A. Langell, "Auger Parameter Studies of Selected Titanium Compounds", 33rd Midwest Regional Meeting of the American Chemical Society, Wichita, KS, November 1998.
9. J.W. Choi, "Very Thin Crystalline Functional Group Copolymer(Vinylidene Fluoride-Trifluoroethylene) Film Patterning Using Synchrotron Radiation", *Materials Research Society Fall Meeting*, Nov. 29, 1999, Boston, Abstract FF4.7 .
10. S. Adenwalla, P. Welsch, A. Harken, J.I. Brand, A. Sezer and B.W. Robertson, "Characterization of PECVD Boron-Carbide Materials and B-C/SiC Diodes", 5th High Temperature Electronics Conference (HiTEC), Albuquerque, June 2000.
11. D.L. Pugmire, C.M. Woodbridge and M.A. Langell, "Adsorption of Nickelocene on Si(111)", 219th National Meeting of the American Chemical Society, San Francisco, March 28, 2000.
12. M.A. Langell, C.M. Woodbridge, D.L. Pugmire and N. M. Boag, "Adsorption and Decomposition of Decamethylferrocene on Ag(100), 219th National Meeting of the American Chemical Society, San Francisco, March 28, 2000.
13. D.L. Pugmire, "Nickelocene Decomposition and Decomposition on Single Crystal Surfaces", Invited Talk , NIST, June 23, 2000.

VII. INVENTIONS AND PATENTS

The University of Nebraska has obtained permission from the board of regents to pursue patents related to our work over the course of this grant. The University has requested and received permission from AFOSR to file five patents AFOSR. Two have been approved by the US Patent Office and have been issued; three are in various stages of evaluation.

Patents:

1. P.A. Dowben, "Forming $B_{1-x}C_x$ Semiconductor Layers by Chemical Vapor Deposition", US Patent Number 5,658,834 issued Aug. 19, 1997.
2. P.A. Dowben, "Boron-Carbide and Boron Rich Rhombohedral Based Transistors and Tunnel Diodes", US Patent 6,025,611, issued Feb. 15, 2000.
3. Shireen Adenwalla, B.W. Robertson, and P.A. Dowben, "Method and Device for a Novel Solid State Neutron Detector"; 60/109,898; filed November 25, 1998; Shook, Hardy and Bacon's file UNVN.62457; Shireen Adenwalla, B.W. Robertson, and P.A. Dowben, "Boron-Carbide Solid State Neutron Detector and Method of Using Same", Patent Cooperation Treaty Application, filed November 25 1999.
4. Harish M. Manohara, Phillip T. Sprunger, and Jaewu Choi, "X-ray Pattern Transfer in Poly(Vinylidene Fluoride), and Poly(Vinylidene Fluoride) X-ray Masks", US Patent Applied for, filed on June 25, 1999.
5. P.A. Dowben, "Boron-Carbide and Boron Rich Rhombohedral Based Transistors and Tunnel Diodes II", 09/465,044, filed Dec. 15, 1999, Suiter and Associate's file UNL 96-11-4.

VIII. HONORS AND AWARDS

Mr. David Pugmire (now Dr. Pugmire) received national accolades from the American Vacuum Society (AVS) in the form of an AVS Graduate Research Award in 1999 for research sponsored by this grant. His present position at NIST is funded by the competitive National Research Council Postdoctoral Fellowship program. His Ph.D. thesis (May 2000) was awarded the University of Nebraska's Folsom Award for Distinguished Dissertation, presented to Dr. Pugmire in April 2001. He also received a first place presentation award for a poster at the Rocky Mountain AVS regional meeting (August 1999).