



WATKINS-JOHNSON COMPANY

Tech-notes

Atmospheric Pressure vs. Low Pressure Chemical Vapor Deposition



Electrical circuitry has been evolving to cope with ever-increasing product-design complexity. Along with product-design complexity has come pressure to fit more and more circuit functions in smaller spaces. Although many of today's technical applications find themselves cramped for space, electronics is the leader in achieving functional density, as conductors and insulators approach dimensions of a few atoms.

Ordinary household wiring is an example of low-tech circuitry. The traditional "wire" is a thin, round rod, although the wire and conductor can be of any shape. Today's circuits, especially complicated ones, are printed patterns rather than complex networks of wires.

The printing on this page is a set of recognizable optical patterns. The paper is an insulator on which modern printing can produce extremely complex, repeatable patterns. If the ink were electrically conductive, it could just as easily be a circuit pattern.

Lithography

Modern printing often utilizes a technique called lithography, which means "stone printing." Lithography was invented by Alois Senefelder in 1796. He discovered that polished stone could be changed from ink-repelling to ink-receptive by acid etching. By engraving a waxed stone, he could acid-etch selected areas and make a durable stone printing plate. In his case, the wax coating had to be laboriously hand engraved. The greater the detail, the greater the labor. Fine detail was, and is, fairly limited. Many other materials have been found to respond to this process, but the name "stone printing" is still used. This basic technique is used in circuitry as well.

In the more modern process, photolithography, the wax is replaced by a photosensitive lacquer (photoresist). The pattern artwork can be drawn on any surface and in any convenient or highly magnified size to handle extremely fine detail. The pattern is then photographed and reproduced to any scale desirable, down to the optical resolution of the lens system. When the image is projected on the photoresist, an exposure pattern is produced which is solvent-removeable. The underlying material, be it stone or silicon wafer, can now be subjected to selective chemical etching. Patterns produced this way can be so fine that examination requires electron microscopy (ordinary optical microscopy is inadequate).

Screen Printing

Another technique, silk-screen printing, emerged in China around the year 500. A panel of silk was lacquered or varnished to make it impervious to ink. Ink could be squeezed through unvarnished areas, however, onto an adjacent surface to make an easily reproduced pattern.

Printed-Circuit Boards

The January/February 1991 issue of Tech-notes reported on methods of attaching circuit components to printed-circuit boards. The "board" is a fiberglass sheet to which has been bonded a thin (.003 to .005 inch) sheet of copper. In making a printed-circuit board, a waxy (protective) ink is screen-printed on the copper in the desired pattern. This is analogous to the waxing of the lithography stone, but eliminates the tedious engraving. The uncovered copper is removed by acid, the waxy ink by solvent.

Circuit Resolution

Patterns made this way typically get no smaller than 0.020 inches (500

microns) in feature sizes. The screen-printing scheme can be pushed a little smaller when the ink itself is compounded to be the circuit material. In that case, the ink is printed onto a thin ceramic plate. The ink is cured and bonded by furnace firing. This is the "thick-film firing" application for which many standard furnaces are used. The circuit pattern is produced directly by printing. No etching or resist removal is required. Thick-film circuit features get down to about 0.005 inches (125 microns) in width and .001 inch (25 microns) in thickness.

Circuit Density

Figure 1 illustrates the significant conductor size reduction in going from low-tech circuitry (the household wiring example), to printed circuitry, to thick-film. The idea, of course, is to make circuits smaller or to fit more circuitry into the same space. A wire is round, but the conductors on PC boards tend to be flat rectangles. Wires tend to go from connection-to-connection in three-dimensional space, whereas printed circuits are mostly flat (two-dimensional). In two dimensions, if the conductor and the insulating spaces get ten times smaller, the overall circuit is 100 times smaller because both length and width are affected. Small changes thus tend to bring big circuit benefits. From Figure 1, one might estimate the thick-film element to be 100 or 1000 times smaller than household wiring, thus 10,000 to one million times smaller for the same circuit.

Thin Film

As dramatic as thick-film circuit resolution sounds, it doesn't stop there. Beyond printed thick film, conductors can be made of thin films which are about one fiftieth of one thousandth of an inch thick (one half micron) and

are typically about one micron wide. This is a barely detectable speck on the scale of Figure 1. Even in the regime of thin film, the pressure is on to achieve ever smaller dimensions.

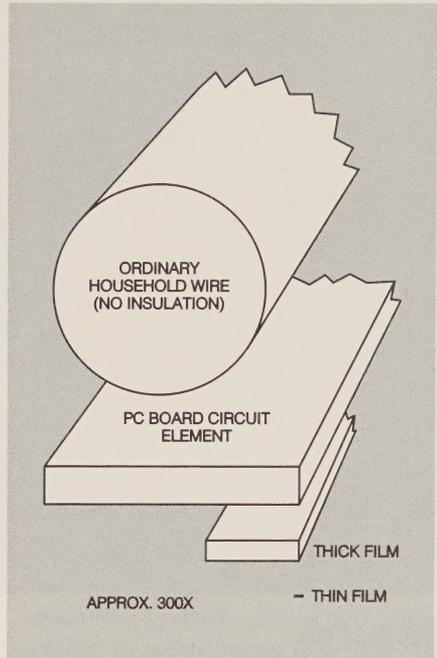


Figure 1. Evolution of electric circuitry. Top shows an ordinary household wire (12 Gauge, no insulation). Below that is a portion of printed circuitry, then thick-film and finally, thin-film microcircuitry.

Circuitry vs. the Brain

In today's advanced stage of technology, microcircuits are being compared to nerve fibers. It's generally accepted, however, that microcircuitry has to get ten million times more sophisticated before it can rival the human brain. Any one nerve fiber is about ten microns in diameter. Although microcircuit features are now smaller than nerve fibers, nervous system interconnects are far more complex, plus they're made in three dimensions, not two dimensions (see Figure 2).

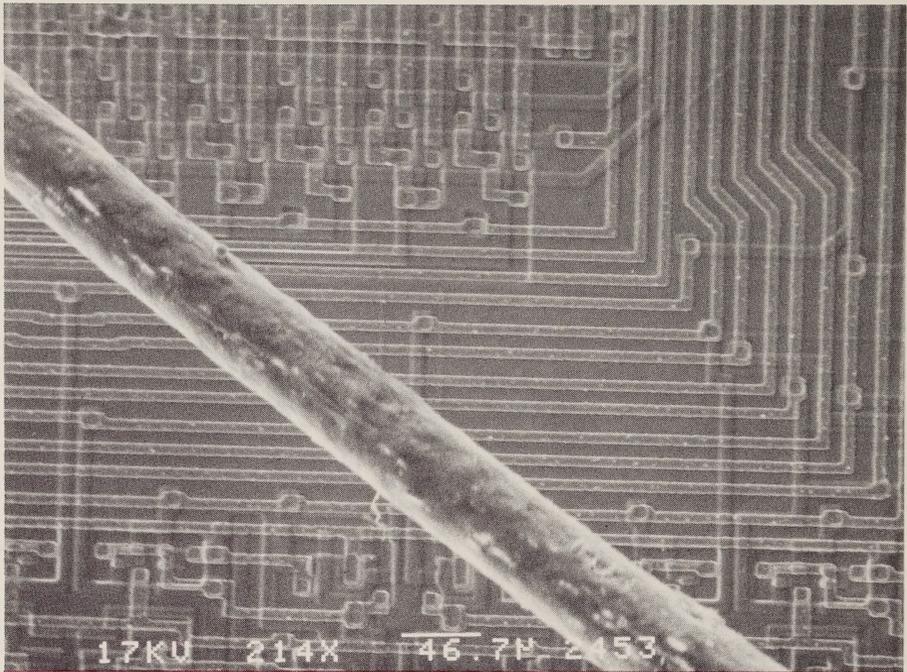


Figure 2. A human hair superimposed over semiconductor circuitry. The photo is somewhat out of date, in that today's circuits are 400 times smaller (i.e., the same circuit is 20 times smaller in length and width).

Perfection

When circuit features get extremely small, the material out of which the circuits are made must reach a high degree of perfection. Small defects such as microscopic cracks, pinholes or dirt particles would severely damage the circuit. This is the reason such extreme cleanliness measures must be taken in semiconductor manufacturing. It is also the reason for constant research and development to get the coatings ever closer to absolute microscopic perfection. As circuits become ever smaller, one wonders, "How small is small?" and "What is the ultimate surface?"

In Figure 3 (Courtesy of IBM), IBM scientists positioned individual xenon atoms on a nickel crystal surface. Rows of nickel atoms making up the crystal are faintly evident. Magnifica-

tion is about six million. Clearly, a surface is not the hard, smooth boundary it appears to be. It is a transition zone of atomic nebulosities. IBM went to great extremes in achieving such individual control of atoms. Typically, the atomic scale makeup of any surface is unknown. Yet, this is the region where many vital phenomena take place. In CVD deposition, gaseous atoms or molecules interact one-by-one at the surface in building up the coating. Although microcircuits are not this small, dimensional control of ten atoms or so is not uncommon.

Vacuum Deposition of Thin Films

Traditionally, thin films for microcircuits are made in vacuum chambers by various evaporation techniques. Evaporation renders the film-forming

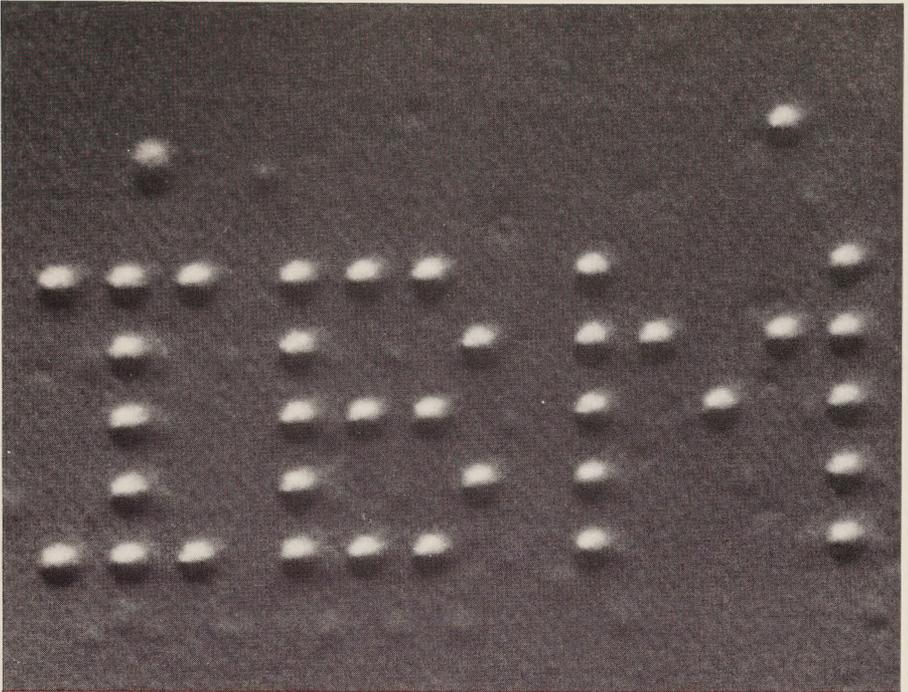


Figure 3. The true nature of surface.

(Courtesy of IBM)

material gaseous. On the surface to be coated, atom-by-atom condensation of this evaporant forms the thin film. The vacuum deposition process tends to be expensive and cumbersome in production, but more conventional techniques (such as mechanical rolling, electroplating, or paint-like coating) are totally inadequate when examined microscopically. The cost and production inadequacies of the vacuum process have, thus, been largely accepted. If the highest possible control is mandatory, it would seem that vacuum is also mandatory.

Advantages of Vacuum

Part of the logical appeal of vacuum is that nothing could be cleaner than absolute emptiness. Also, if air itself, or the moisture or pollutants it contains is a contaminant, then vacuum is necessary to get rid of it. In addition,

one of the greatest sources of contamination in clean rooms is people—the workers. Flakes of skin, organic vapors, fibers, bits of hair, and breath and smoke residues are all attributed to people. Since people can't co-exist in the vacuum chamber, vacuum provides protection from people.

Limitations of Vacuum

Where extreme control is necessary, the merits of vacuum seem so strong that any other method would be an undesirable compromise. However, a closer look shows that there are problems, even serious problems, with vacuum and that there are more advantages than expected with atmospheric pressure.

First of all, a vacuum is never "empty." Even an exotic vacuum can't remove all the gases. Even outer space isn't

totally empty. Vacuum as a pressure concept is, thus, never zero but is some fraction of atmospheric pressure. It makes sense that while one might achieve a feeling of accomplishment in generating a high vacuum, one has to be concerned about what's left, not about what's gone. At a billionth of an atmosphere (respectable but not exotic) there's still 30 billion molecules flying around in every cubic centimeter. Every surface atom on a super-clean silicon wafer would experience collision or chemical reaction with one of these molecules each second. This is the way surface contamination occurs. While it's true that the same kind of contamination would occur at atmospheric pressure a billion times faster, it's little consolation that by resorting to vacuum, contamination has been avoided for a mere second.

Limitations of Vacuum Materials

Why can't a vacuum system be truly empty? Why can't the pressure be truly zero? First of all, everything (in or out of vacuum) has a tendency to evaporate without needing to liquify; like mothballs or dry ice (sublimation). Nothing could serve as a container for a perfect vacuum because the container itself vaporizes to contribute to the residual gases. Similarly, no materials are absolutely impermeable. Gases from the outside slowly seep (diffuse) through the walls of any vacuum enclosure.

For well-chosen and well-processed materials, sublimation and diffusion effects can be kept small. A bigger limitation comes from the fact that no materials are pure or ideal. All materials contain volatile components to some degree and all materials adsorb gases on their surfaces. These volatiles are gradually liberated under vacuum conditions, frustrating the

work of the pumps. The harder you try, the more difficult it tends to get, because the lower the pressure (the higher the vacuum) the smaller the amount of gas required to oppose your efforts.

Gases

All gases consist of freely moving atoms or molecules. Their number in any given space is the real meaning of pressure, and their velocity is the real meaning of temperature. So any "gas" is composed of tiny specks shooting through a perfect vacuum at rifle-bullet speeds. Since there are so many others around, these specks don't go very far before they collide with (and bounce off) another one. This distance is the mean free path (MFP). At atmospheric pressure, MFP is about one millionth of an inch. At one tenth atmospheric pressure, MFP is ten times longer (inversely proportional to pressure). Because of all the collisions, a gas molecule doesn't get from point A to B at rifle-bullet speeds. Its random fractured rebound motion from point A to B is its diffusion, which at atmospheric pressure is about one inch per second. At one tenth atmospheric pressure, diffusion goes to ten inches per second (proportional to MFP).

Diffusion occurs even in gases that are perfectly still. If there is a pressure gradient, the whole body of gas will move in response to it. Diffusion is totally independent of bulk flow, even moving up stream. Once pressure flow exceeds diffusion flow, however, no net upstream diffusion flow can occur. This, on an atomic scale, is what is going on when a container is purged or flushed with clean gas. Conversely, flushing action cannot be accomplished unless diffusion velocity is exceeded.

In some cases, the object of vacuum is

to avoid diffusion collisions. Vacuum electron tubes, nuclear particle accelerators, electron microscopes and thermal insulation are examples. MFP under such conditions is very long and diffusion rate approaches rifle-bullet speeds. Thin-film coatings, however, are not vitally dependent on long MFP. Are there any aspects of vacuum inherently beneficial to coatings or is it simply a matter of contamination control?

Shadowing

Objects to be coated often have complex non-flat surfaces. Since vacuum deposition tends to be line-of-sight (a consequence of long MFP), some surface areas can be poorly coated if shadowed by others. Planetary fixturing, or other means of randomizing deposition, can help, but shadowing is a troublesome characteristic. As circuits get more complex, the problem gets worse. The viscous flow associated with higher pressure (shorter MFP) reduces shadowing because flow under these conditions carries material around corners.

Radiation Damage

Sputtering processes (evaporation induced by ion bombardment) depend on complex electronics which produce complex electromagnetic fields. The ion and electron activity risks damage (by bombardment) to semiconductor substrates. This, too, is a more serious problem with newer microcircuit structures.

Gases and Contamination

When it comes to contamination, some gases are more objectionable than others; some gases are totally inert and still others are beneficial. Most of the time, concern centers around water vapor, carbon dioxide, carbon monox-

ide and organics as common, difficult-to-avoid contaminants. In ordinary air, the 80% nitrogen is often inert but the 20% oxygen is the problem.

When typical residual vacuum gases are analyzed (see Figure 4), they are found to contain about 70% objectionable species. They are the result of outgassing and degassing and are difficult to eliminate. Deposition in vacuum tends to be slow, as the rate is a function of pressure. This gives contaminants more time to do their damage. Furthermore, because of long MFP and high diffusion rate, any contamination source in the whole vacuum system tends to have easy access to the deposition area.

It is a credit to the problem-solving accomplishments of those working in vacuum technology over the past 100 years that, in spite of so many limitations, vacuum processes are so widely used. Vacuum, however, is more complicated than atmospheric pressure. Atmospheric pressure processing isn't necessarily simple, but pressures below (or above) atmospheric are less simple and, thus, unfavorably impact cost and productivity. A powerful precedent is set in that the brain, the ultimate in microcircuitry, requires no vacuum. A complex product doesn't necessarily require more complex processing.

CVD

In the 1940's another deposition method began to appear. One of the early workers with this method was John Blocher, now retired from Battelle Memorial Institute. Gaseous sources of deposition material are used. By comparison, in vacuum deposition, the source material is solid, rendered gaseous by heat or ion bombardment. Gaseous sources can be more highly purified than solid targets. There is also the opportunity, using gaseous

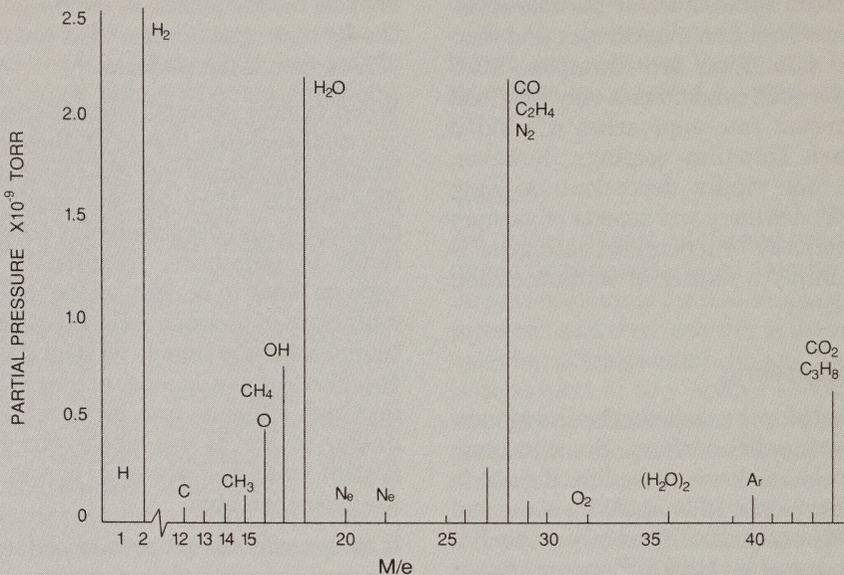
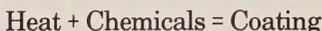


Figure 4. Residual gas spectrum (10^{-8} Torr). Typical gases remaining in a vacuum chamber.

sources, for greater variety of chemical trickery in obtaining desired results. It's one thing to vacuum-deposit *elements*, for example, but another to deposit *compounds*. Energy utilized in subliming solid targets is often sufficient to dissociate molecules, disrupting the basic makeup of the coating material. "Reactive sputtering," a deposition technique designed to address this problem, is used to get fractured molecules back together again.

John Blocher's technique, chemical vapor deposition (CVD), is elegantly simple in concept.



Heat is used to destroy (pyrolyze) gaseous molecules, leaving behind solid residues as a coating.

Although simple in concept, it can still be quite difficult to meet all the tough specifications expected of the coating.

Partial Pressure

Of course, contamination is an important CVD issue, as with any coating technique. The chemicals must be very pure since the coating cannot be any purer than the materials it's made from. However, another concept is emerging here. *Purification* means getting rid of only the contaminants. Vacuum techniques, on the other hand, strive for purity (contamination control) by removing everything. If it were indeed possible to remove everything, it would also not be possible to produce a coating since there are no ingredients. One could argue that vacuum evaporation doesn't require gaseous ingredients. But the purity of the solid source cannot be enhanced by the vacuum system no matter how low the pressure is. It is not so much the total pressure which matters. It is not so much vacuum or atmospheric or above atmospheric which matters, it's the

partial pressure of the contaminants. In the 1960's, primitive atmospheric pressure (AP) technology did not compare well to advanced low pressure (LP) technology. But that was a comparison of the level of development. Partial pressure control at that time favored LP. Whether AP or LP, sophisticated results require sophisticated equipment. Whether AP or LP, it comes down to doing the job properly to get the desired results.

Containment

It is expected that any complex process should be carried out in an enclosure so that process conditions can be controlled and maintained. If the process can be carried out at atmospheric pressure, one important advantage, especially for production, is that work can be brought comparatively easily in and out of the enclosure. It would seem that every effort should be made to process at atmospheric pressure before resorting to pressures above or below atmospheric. If desired results can be achieved at atmospheric pressure, what is the point of higher or lower pressure? Developments at Watkins-Johnson Company have shown that desired results can indeed be achieved at atmospheric pressure, and that these methods work effectively in production.

LP and PECVD

CVD is a technique which works at any pressure, not just AP. Low pressure (LPCVD) and plasma-enhanced low pressure (PELPCVD) are also commonly used. A disadvantage of LPCVD is that chemical debris must be swallowed by the necessarily sophisticated vacuum pumps. It is a remarkable accomplishment that pumps are available which tolerate such abuse. It is widely believed that low pressure may

have an advantage in particle formation and contamination. However, the reality seems to be that vacuum conditions, where no chemical source particles form, is a condition where no coating forms either. Experience has shown that particle control at AP is quite competitive with LP.

Early APCVD for Electronics

The electronics industry experienced great expansion in the '50s and '60s. Defense application fueled much of this expansion and was a key factor in the formation of Watkins-Johnson Company. The conveyor belt furnace emerged in the mid '60s to meet the growing requirement for more production-oriented equipment, primarily for printed-circuit board and thick-film applications (the big volume, low-cost part of the industry). Also in the 1960's, much work was being done (by other companies) to perfect APCVD apparatus and processes for electronic applications. This work was largely unsuccessful and left many people with the impression that atmospheric pressure simply was not adequate for the task. Three unsolved problems seemed to be at the heart of this failure:

1. A chemical delivery nozzle sufficiently accurate to form accurate coatings was needed.
2. An enclosure design which could protect the process area from work-room disturbances (air contamination, drafts, etc.) was necessary.
3. A process for accurate removal of chemical by-products was required. (Too fast removal wastes chemical and thins the coating; too slow, fouls the process.)

Problem 1 caused a shift towards low pressure. Rapid dispersion of gases

(when injected into a vacuum) was used as a means of improving uniformity.

Problem 2 caused a shift towards a hermetic enclosure to seal out room disturbances.

Problem 3 was resolved by simultaneously controlling gas inlet flow and vacuum pumping speed.

The result, LPCVD, was more a failure to solve the above three problems at atmospheric pressure than a recognition of something inherently superior about LP.

Early CVD at W-J

In the early 1970's, Watkins-Johnson Company began looking at combining CVD with its conveyor furnace. This work began at the urging of early digital display makers who needed the cost effective production-oriented features of conveyor furnaces for their manufacturing requirements. There were only a half dozen or so conveyor furnace makers in the whole world they could turn to. The furnace embodies a significant amount of technology in itself. CVD is also a significant technology by itself. Developing both, simultaneously, could be overwhelmingly difficult, but Watkins-Johnson Company soon developed significant CVD proficiency.

The three problems, listed above, were solved by:

1. Development of a unique nozzle (injector) with performance features which reach semiconductor specifications. The injector is totally manufactured at Watkins-Johnson, using equipment and techniques developed at Watkins-Johnson.
2. Experience with elaborate furnace muffle structures provided a launch point for still greater sophistica-

tion. CVD muffles can now provide the required process protection and work-room isolation without having to be hermetic.

3. A unique self-cleaning vent-line flow meter has been developed which provides controlled by-product removal.

CVD Evolution at W-J

Early digital display coating requirements were quite a bit less stringent than those for semiconductors. The first Watkins-Johnson Company CVD furnace was sold in 1975 and it is still in display-making service. Overall proficiency improved to the point where in the early 1980's semiconductor applications could be considered. The conveyor furnace, originally for thick film, had now become thin-film qualified.

A major milestone in the mid 1980's was the successful demonstration of borophospho-silicate glass (BPSG) coatings. No low-pressure process has yet been able to demonstrate full production practicality. For the first time, an atmospheric pressure process was (at least for BPSG) *superior* to vacuum. [3].

LP Limitations

The BPSG achievement brought further awareness to inherent limitations of low-pressure techniques. Batch processing was necessary at low pressure because low LP coating rates could not otherwise keep up with production. While 100 wafers at a time was okay for smaller wafers and simpler circuits, it's not okay today. The problem is that the same coating conditions can not be delivered to each of the batched wafers. Gas phase reaction plus coating depletion rapidly changes the gas composition as it flows over the wafers. In addition, larger wafers

disturb flow patterns and mask each other more severely than small ones. Another factor is that complex coatings, especially from organic precursors, need large oxygen excess to react properly. In a vacuum system, excessive oxygen results in depression of deposition chemicals, causing lower deposition rate, further aggravating an already-low deposition rate problem.

Single Wafer

These developments shook the LP industry to where batch processes have now all been abandoned in favor of single wafer. Conveyorized APCVD is essentially single wafer in the sense that all wafers get the same treatment. It's obtained quite naturally at AP while it's quite a struggle at LP. LP processes have been gradually rising in pressure to increase deposition rate. Some approaching atmospheric pressure are called "high pressure" or "sub-atmospheric."

Non-Oxide Coatings

One advantage to vacuum processing had been in the preparation of oxygen-sensitive films. Metal or silicon films, for example, would be severely contaminated by air getting into the open ends of conveyorized CVD. For a while it was thought that APCVD might only be suitable for oxides; all others would need LP. However, development during the '80s has shown this isn't so [4]. The reason gets back to the nature of diffusion. It was pointed out earlier that coating processes, vacuum or otherwise, are crucially dependent on source material purity. If a shower of similarly pure inert gas (carrier gas) covers the process area, outside air (or any other contaminant) can not get in, provided the flow velocity exceeds diffusion velocity (see Figure 5). Since diffusion velocity is only one inch per

second at atmospheric pressure, modest flows are sufficient to provide protection. The belt and its load of wafers go in the muffle, but air doesn't. This is quite a nice atmospheric advantage. Anything comparable at LP requires complicated interlocks. Diffusion works for you at AP but against you at LP. This is the reason oil backstreaming is a common vacuum problem. There are non-oily pumps but the oily ones tend to be the good work horses.

Purity

There has certainly been increased attention given to gas and chemical purity in recent years. The availability, in large production, of high-purity cyrogenic nitrogen has been an impressive industrial feat. The emergence of chemical getter point-of-use style gas polishing filters has been another impressive development. What is happening is that the reduction in *partial* pressure of impurities is progressing faster than the ability of vacuum systems to reduce *total* pressure. Some chemical getter filters can now reduce oxidizing impurities in nitrogen to levels lower than the best ultra-high vacuum systems. While exotically cleaned piping is mandatory just as in ultra-high vacuum, the role of low total pressure (vs. low partial pressure) is becoming uncertain except where long mean-free-path is required.

Low-Temperature Deposition

An important advantage of plasma-enhanced low-pressure CVD (and to some extent photo-enhanced CVD) is the ability to induce low-temperature deposition. APCVD, which is simply thermally induced, requires, for example, about 650°C to make silicon nitride, whereas plasma works at about 250°C. There are some qualifications, however. Plasma nitride, al-

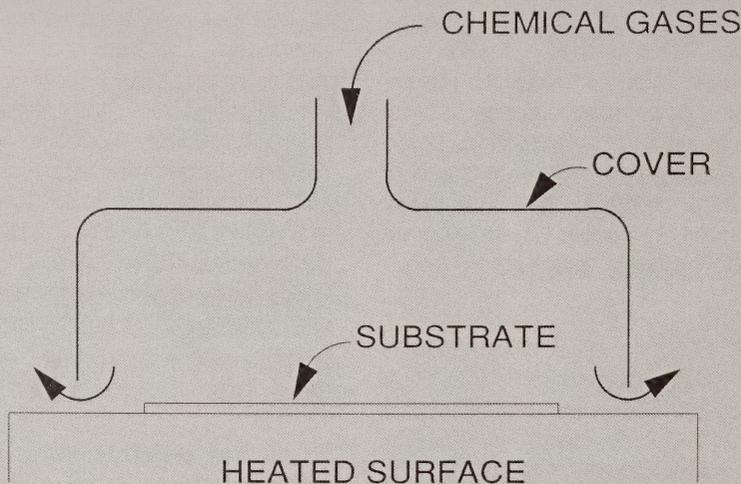


Figure 5. Diagram showing simple cover keeping air away from process. As long as flow out of the cover edge exceeds diffusion flow (about one-inch per second), no surrounding air or contaminant can get under the cover.

though it is useful material, is not really silicon nitride. The proportions of silicon and nitrogen vary; oxygen is often present, and hydrogen is almost invariably present. The hydrogen may be given off in subsequent processing, causing damage to the microcircuit structure. Plasma processing tends to be slow, have particle problems and, of course, risk radiation (ion or electron bombardment) damage. Still, when process temperature is a crucial factor, plasma has a clear advantage.

Atmospheric Plasma

Plasma doesn't have to be a low-pressure process. It is simply a matter of coincidence that a plasma is easier to generate at one thousandth of an atmosphere or so. Free electron mean-free-path at this pressure provides an optimum for easy ignition. Lasers, x-rays, nuclear radiation, corona discharges and sparks can produce plasmas at atmospheric pressure, but relatively little work has been done to associate them with deposition. One of the new

deposition techniques depends on corona discharge at atmospheric pressure to generate point-of-use ozone. Deposition is radically altered towards lower temperature by ozone vs. oxygen. The point is that plasma and AP are not mutually exclusive. Ozone is one example of atmospheric plasma and is likely to lead to others. There has also been some chemical solution to deposition temperature reduction.

Precursors

In the 1950's, when microcircuit technology was developing, the usual precursor for silicon dioxide films was ethyl silicate (more correctly, tetra ethyl ortho silicate; TEOS). The deposition temperature, 800°C or so, was undesirably high, prompting a search for a better-behaved chemical. Silane was considered the answer. A long and substantial silane-based industry resulted. Interestingly, because of its superior conformality on cramped modern circuitry, plus temperature reduction brought by ozone, silane is

now being upstaged by TEOS. Another intriguing example is the development at Harvard University of titanium nitride precursors which work at 200°C and at atmospheric pressure. Precursors for low temperature AP, silicon nitride may not be far behind.

Liquid Source

TEOS ozone and BPSG from liquid sources (reacted with ozone) is the object of Watkins-Johnson Company's newest CVD furnace design. Intense equipment design and process development has occurred, and with marked success, in response to the industry's urgent need for improved conformality and reduced process temperature [5].

Conclusions

The TEOS ozone CVD furnace is but the newest of a long series of developments spanning the whole history of Watkins-Johnson Company. Furnaces began in the early 1950's as laboratory specials for Stanford University by Ray Stewart (Founder of Stewart Engineering which became W-J Stewart Division in 1964). He used a primitive form of CVD as early as 1960 (charge dissipating coating of tin oxide, inside backward wave oscillator glass vacuum envelopes). Conveyor furnaces emerged in the mid-sixties and conveyorized CVD in the early '70's.

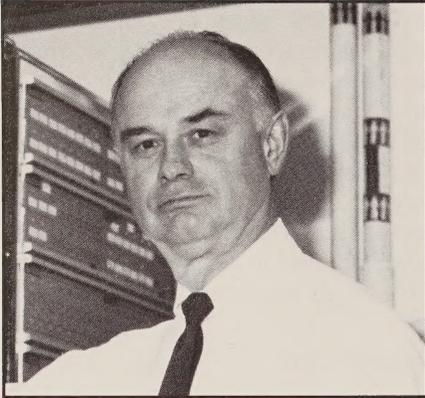
Today, CVD is primarily focused on electronics. But that's just the beginning. Substantial growth potential exists. Without the restrictions of vacuum, heavy industry can also be served. Watkins-Johnson Company already interacts in small ways in flat panel displays, solar energy, architectural glass, lighting and protective coatings. There are applications in smart mirrors, smart windows, auto-

motive windshields, fiber optics, copying machines, thin-film electronic devices, new types of thin-film circuitry, coatings on plastic, wear, abrasion, corrosion resistant coatings and so on. So many applications arise from the fact that coatings always upgrade the performance of a substrate in some way. The world we live in is a vast array of surfaces which could all stand to be improved in some way. Truly, we have barely scratched these surfaces.

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He is involved in many of the ongoing CVD development projects. He has written numerous technical papers and presented talks on the subject of CVD. He interfaces with Marketing and Sales to keep technical feasibility in line with customer needs.

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