CVD process engineering: modelling aspects

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Abstract

After a long period of time during which CVD industrial reactors have been developed only by empirical ways, theoretical analysis and modeling of their behavior have opened new possibilities for practicing engineers. These new methods are discussed in details in the paper with a particular emphasis on the analysis of chemical phenomena, as well in the gas phase as on surfaces, and a discussion of the advantages and drawbacks of several reactors in use in the microelectronics industries.

The main limitations of CVD modeling and numerical simulation are first that such a procedure cannot be used when the corresponding chemistry is too complex and, second, that it provides no information on the deposits structure and properties. As a consequence, the paper ends by a discussion on the organization of the unavoidable experiments in the design procedure of a particular equipment and its operating conditions.

Among the chemical vapor deposition very numerous applications, those related to the corrosion or erosion protection of mechanical pieces and those in the microelectronics field deserve a special mention in reason of their industrial importance. These two examples largely suffice to suggest that a non negligible part of modern nations prosperity depends, today, and will increasingly depend, in the future, on their ability to master CVD methods and technologies.

This economic importance constitutes a first reason to analyze the present state of the art in CVD engineering.

The second reason is linked to the fact that this particular scientific field has been improving very rapidly in the past few years. It has begun to move from quite pure empiricism to a more scientific approach which involves a systematic analysis of the fundamental steps constituting CVD operations then their complete modeling. Thus, it seems to be a good time to evaluate these new methods and their consequences for industry.

In such a context, I have considered the invitation of the organizers of this conference as an opportunity to present my personal opinion on this subject. As a consequence, my paper will be neither objective nor complete. It is, by no way, a literature survey and the few references given at the end of the text have been selected, as examples, in the works that my colleagues and myself are doing in Toulouse. In spite of all these limitations, I hope that some of the ideas I am going to present will be of value for, at least, one part of the audience.

1. ON CVD INDUSTRIAL REACTORS EXISTING TECHNOLOGIES

More or less, a CVD reactor always appears as an enclosure in which convenient gases are put into contact with hot substrates. Depending on the particular CVD case considered, the reactor walls themselves can be, either hot -this is then a so called hot wall reactor -or cold- this is the category of cold-wall equipments.

The most frequently used apparatus in the microelectronics industries is the horizontal tubular hot wall reactor, which is schematically presented on figure 1.

The main interest of this technology is that it offers the possibility to treat, simultaneously, a large number of substrates with a convenient uniformity as well in thickness as in properties, either on each wafer or on the batch.

Fig. 1.

Fig. 2

Unfortunately, such an equipment has revealed to be inadequate for several treatments, for example epitaxy or metal-organic CVD. In these cases, experiments have demonstrated that cold wall equipments are more successful; a few of the empirically developed reactors in this class are presented on figure 2. Let me recall that cold wall apparatuses are much more difficult to operate than hot wall ones, which prevents them from treating important batches at each operation. Productivity being much lower, production costs increase noticeably; cold wall reactors must be selected only on the ground of mandatory technical reasons.

In cold wall equipments, a special mention must be made of rapid thermal processing equipments. These reactors, of the single wafer type, are heated by radiation so that the increase in temperature and, to a lesser extent, the decrease be very rapid. As consequence of their very low thermal inertia, it becomes possible to control their functioning by action on the heating lamps. This gives to RT reactors a great flexibility, particularly interesting for fine productions, by short campaigns, when it becomes economically impossible to build a dedicated reactor for each deposition case.

This very rapid presentation of the main categories of industrial equipments for CVD will be followed, now, by a much more detailed discussion of their operation characteristics, of their possibilities and limits.

2. KINETICALLY SIGNIFICANT STEPS IN A CVD OPERATION

Till now, the design of industrial CVD equipments and the choice of their operating conditions have been performed quite exclusively by long, tedious and expensive series of experiments. If this empirical treatment has produced very interesting results, it begins to reach its limits and do not always provide convenient solutions to the increasingly difficult modern CVD problems.

It is, thus interesting to move to more scientific and rational methods, i.e. modeling and simulation and, in a first step, to list, briefly, all the basic phenomena that can be involved in a chemical vapor deposition; they are schematically represented on figure 3.

Fig. 3

A first group of phenomena takes place in the gas phase. They comprise gas flow, from the entrance into the reactor to the substrates surfaces, gas heating, eventually gas phase chemical reactions, such as pyrolysis or interactions between two species, then mass transport by diffusion and convection. All the physical transport phenomena can be theoretically treated, starting from the corresponding well known partial differential equations of conservation. On another hand, chemical reactions must be described by their formula, then, their rate equations.

A second group of important phenomena take place on the substrates surfaces. They involve adsorption of gaseous molecules on surfaces, chemical reactions with the solid matrix, then rearrangements and insertion in the crystalline structure and, finally, gaseous products desorption. These steps are generally poorly known and very often represented, altogether, by a single apparent kinetic equation or data, such as a sticking coefficient.

A complete treatment of all the gas phase and surface phenomena, in complex geometries and with complex operating conditions probably remains out of the scope of today scientific possibilities. But, fortunately, several theoretical advances for simplified cases of tremendous practical interest have now been realized. We are going to analyze some of them.

3. THEORETICAL ANALYSIS AND MODELING OF HOT WALL REACTORS. THE SIMPLEST CASE

Let us begin by the simplest case when the reactor is isothermal (walls, substrates, gas at the same uniform temperature) and gas phase phenomena are negligible or, in other words, when the CVD operation is completely under control of surface chemistry.

In fact, this is a very uncommon case. Nevertheless, it corresponds quite perfectly to the deposition of polycrystalline silicon by silane pyrolysis, a case of huge industrial importance. For that particular operation, the global chemical reaction on surfaces can be written as :

with a reaction rate given by a Langmuir-Hinshelwood type equation

$$r = \frac{k P_{\text{SiH}_4}}{1 + k_1 P_{\text{H}_2} + k_2 P_{\text{SiH}_4}}$$

and kinetic constants that can be found in the literature [1,2].

In industry, this particular CVD operation is quite always performed in hot wall tubular reactors. This equipment can then be treated, very simply, as a series of perfectly mixed tanks, each being at uniform composition. Each ideal stage is constituted by that part of the reactor situated between two successive wafers.

More details on the very classical treatment of this cascade of ideal stages can be found elsewhere [3].

A typical example of results is presented on figure 4.

It is important to observe that the deposition rate slowly decreases from the entrance to the exit of the reactor ; this phenomenon results from the progressive silane consumption and, hence, decrease of the heterogeneous reaction

rate. These variations could be maintained in reasonable limits by increasing the silane flow rate but this constitutes an expensive solution. Another well-known possibility is to create a temperature profile along the reactor, designed to compensate silane consumption ; the limits are, then, that temperature variations induce changes in the crystalline state and, hence, in the thin film properties. As a consequence, the choice of convenient industrial operating conditions always results from a compromise between these two conflicting considerations.

Extensive works, that have been performed in Toulouse, have demonstrated that the simple ideal stages model that has just been presented constitutes a very precise, rapid and efficient tool for practicing engineers. It works very conveniently in the case of pure silicon deposition from silane ; it has been recently improved to treat the more complex operation of *in situ* boron doped silicon deposition from mixtures of silane and boron trichloride [4].

4. COMMENTS

What could have been immediately evident but became clearer, for me, by a systematic use of simulation is that the hot wall tubular reactor is of the parallel flow type : the wafers line and gas flow are in the same direction. The immediate consequence, already discussed, is that when flowing along the wafers line, gas is depleted and deposition rate decreases or, if depletion is compensated by a temperature increase, films properties vary. Our conclusion, in the last paragraph, has been that the choice of adequate industrial conditions of operation must always involve the search of a compromise between thickness and properties antagonist evolutions.

Recognizing this fact, a few years ago, our group in Toulouse has created and patented [5] a new type of equipment, called the annular reactor, which is presented on figure 5. This original organization is, now, of the cross-flow type, with a circular horizontal row of wafers treated by a vertical flow of gas, in an annular volume. In that case, each wafer of the batch receives gas elements at the same velocity, temperature and composition, which results in perfectly identical deposits.

Such a reactor is presently under study in Toulouse with very encouraging results for pure silicon and phosphorus *in situ* doped silicon depositions [6].

Coming to a more general argument, I wanted here to suggest that if the tubular horizontal reactor is, today, the most popular equipment in the microelectronics industries and, on this ground, must be studied in details to improve the operation of the thousands of apparatuses in use, this does not necessarily mean that it constitutes the best equipment possible for the future. The annular reactor, or any other type of equipment that will, one day, be created, could be of higher interest, at least for particular CVD operations.

Fig. 5

5. AND WHEN GAS PHASE PHENOMENA MUST BE TAKEN INTO ACCOUNT ?

With the very remarkable exceptions that have just been treated, of pure or *in situ* boron doped silicon depositions, CVD operations where gas phase phenomena can be neglected reveal uncommon. All the other cases we have been investigating, needed theoretical treatments more detailed than that corresponding to the cascade of perfectly mixed stages already presented.

restricted to a limited but representative part of the reactor, i.e. the volume between two successive wafers, see figure 6.

Computation becomes, then, workable but, in return, such a choice results in difficult boundary problems. Indeed, for a modeling volume in the center of the wafers line, the entrance conditions, which depend on the complete history of the gas from its entrance in the reactor, become unknown.

Fig. 6

This question has been solved by assuming a periodic situation in which phenomena in one compartment are perfectly similar to those in the preceding or in the following : details on this important subject can be found elsewhere [7,8].

The local models, built on the preceding principles, constitute very powerful tools and provide an impressive number of interesting results. Only a very few of them will be now discussed.

For concentrations, calculations demonstrate that, as a first approximate, stable species like silane, hydrogen or higher order silanes are uniformly distributed in the modeling volume. This result supports the use of a perfectly mixed stages cascade in the preceding model.

On the contrary, the very reactive silylene radical presents important concentration variations (fig. 7 and 8). It is far more concentrated in the annular region between the wafers tips and the reactor wall than between the wafers.

Fig. 7

Fig. 8

These variations result from the fact that the annular region presents a high volume to surface ratio, which favors silylene production against consumption ; the situation is opposite in the interwafers region where deposition on surfaces increases more than production.

For deposition, now, figure 9 demonstrates that silane contribution to the film growth rate is much more important than that of silylene.

This result constitutes a second a posteriori justification for the hypothesis made in the preceding model which neglect all gas phase reactions.

Apart from this confirmation, two dimensional modeling is not particularly useful for this simple CVD silicon deposition

Fig. 9

The very general hypothesis that will be made, then, by practically all the authors is that the gas phase total number of moles remains constant throughout the reactor. This hypothesis is supported by the fact that a convenient treatment uniformity can be obtained only if the reacting gas concentration remains approximately constant, that is to say if conversion remains low. This is the well known CVD paradox which states that such an operation works conveniently when it rejects much more unconsumed gas than it uses to deposit on surfaces.

The very important consequence of that molar flow rate constancy hypothesis is that it becomes possible to separate the flow and heat transfer analysis, performed at constant number of moles and the mass transport and chemical conversion analysis developed, then, using the previously calculated velocity and temperature fields.

To end with this general discussion, it is interesting to observe that if the treatment of transport phenomena can present some degree of generality, on the contrary the chemical reactions analysis remains always specific of the nature of the deposit and of the starting gases. As a consequence, the objective of creating a unique program to simulate all CVD possible cases appears, immediately, at least partly unrealistic.

6. THEORETICAL ANALYSIS AND MODELING OF HOT WALL REACTORS - MORE COMPLEX CASES

Except in a few cases, CVD operations ask for a complete local treatment.

For the horizontal tubular reactor, the cylindrical symmetry of the equipment and wafers (centered in the tube) leads to reduce the analysis to two dimensions.

6.1 Pure silicon deposition from silane [7,8]

Let us rework the case of silicon deposition from silane that has just been treated by the ideal stages approach. When entering in more details, it appears that, as soon as it has been sufficiently heated, silane decomposes by pyrolysis, producing the following set of reactions :

Hence, during its flow in the reactor, pure silane transforms into a mixture of silane, silylene, hydrogen and higher order silanes. Of course, in this mixture, all the silicon containing species can deposit on surfaces, according to the following overall chemical paths

The heterogeneous chemical reactions rates are only known for silane (see paragraph 3). As a first approximate, people in our group generally suppose that silylene reacts at an infinite rate and that higher order silanes, including disilane, do not deposit appreciably.

With these chemical informations, it becomes possible to develop a two dimensional model. An immediate problem is that the numerical treatment corresponding to the whole reactor falls completely out of the possibilities of the present computers. Hence, the modeling domain must be

which represents nothing more than an academic example. On the contrary such a detailed analysis becomes mandatory to treat other cases for which gas phase reactions play a far greater role.

6.2. In situ phosphorus doped silicon deposition [9]

It is well known that *in situ* phosphorus doped silicon deposition from mixtures of silane and phosphine constitutes a complex operation. It is also well known that in such a deposition, phosphine or, more probably, phosphorus atoms inserted in the solid film, inhibit strongly the contribution of silane to deposition, while silylene contribution remains unchanged.

Using the preceding modeling results, it is easy to appreciate the consequences :

- the strong decrease of the silane surface reaction rate, which constituted the major contribution to pure silicon deposition, results in a strong decrease of the doped film growth rate,
- the previously secondary and quite negligible contribution of silylene becomes dominant, which enhances the role of gas phase phenomena,
- overthicknesses at the wafer periphery, which remained negligible compared to the overall rate for pure silicon deposition become now significant,
- distance between two successive wafers, which played no role in the deposition of pure silicon, exerts now a strong influence on the deposition rate by controlling the surface over volume ratio in the modeling volume,
- finally, the length of the entrance zone in the reactor, from the front door to the first wafer, which had previously no influence, constitutes now a significant parameter (see figure 10). When this length increases, silane pyrolysis produces higher silylene and disilane concentrations, which result in faster deposition rates. This previously unknown effect has been recently put in evidence by our group [9].

Fig. 10

6.3 Silicon deposition from disilane [10]

Disilane is much more unstable than silane. As a consequence, it decomposes at lower temperature producing higher silylene concentrations. At these lower temperatures, the reactivity of silane and hence, its contribution to deposition appears quite negligible ; silylene plays, now, the dominant role. This complete change in mechanism when replacing silane by disilane leads to several consequences :

- deposition works at far lower temperatures, which is interesting to treat thermosensitive substrates,
- all the characteristics of deposits controlled by gas phase kinetics appear in this case, overthicknesses at the wafer periphery and influence of the interwafers distance (like for phosphorus *in situ* doped silicon from silane),
- the addition of phosphine exerts quite no influence, since the inhibition of the silane contribution concerns a phenomenon which is completely secondary ; on the contrary, the main contribution, that of silylene, and hence the total deposition rate remain unchanged.

It is interesting to observe that silicon depositions from monosilane and disilane have been treated with exactly the same methods and the same chemical mechanisms and kinetic data, which increases greatly the confidence which can be afforded to such a modeling procedure.

7. COMMENTS

The cases which have been presented demonstrate that local two dimensional modeling of CVD operations in tubular hot wall reactors is possible and provide important and interesting results.

The main difficulty, which prevents from developing immediately similar procedures to treat a lot of other CVD operations, is a dramatic lack of chemical knowledge. It is easy, for everybody, to observe that in most cases, the only information is an overall surface reaction scheme, of course completely insufficient for a correct theoretical approach.

Hence, it appears that the future of CVD engineering, by modeling then numerical simulation, asks for important advances in chemistry. What is needed is, first, chemical pathways enough detailed to represent conveniently the main features and at the same time with a limited number of species and reactions to simplify calculations, then the corresponding kinetical laws.

On this last subject, it is interesting to add that a few prediction methods can be of help for homogeneous reactions, as well to adapt to the CVD conditions data measured in other temperature or pressure conditions or, eventually, to evaluate first approximates when results are completely lacking. Of this type, the Quantum Rice Ramberger and Kassel method begins to be largely used [11].

On the other hand, the question of heterogeneous kinetics appears more difficult to solve ; no convenient prediction methods seem at hand. Hence, a theoretical effort on that subject would be of value.

The following paragraph will present an additional example of CVD theoretical treatment which involves a complex chemistry.

8. ON SIPOS CVD MODELING [12]

The phenomena and, hence, theoretical treatments become more complicated than discussed till now when two or more gases are involved in the deposition and interact, previously, in the gas phase. Let me say a few words of the particular case of SIPOS, we are presently studying in Toulouse.

What is called SIPOS or semi-insulating polycrystalline silicon is in fact an intermediate species between silicon and silicon dioxide, of global formula SiO_x , obtained by pyrolysis of a mixture of silane and nitrous oxide. The main interest of this material is that its degree of oxidation and, hence, its insulating properties can be adjusted by action on the silane to nitrous oxide ratio, so facilitating the design of electric field repartitors and increasing the breakage voltage in power components [13].

From a theoretical and modeling point of view, now, a long trial and error procedure has been necessary to select the following homogeneous simplified chemical mechanism :

which involves seven species and four reactions. Except for the second reaction, all the kinetical constants have been calculated by the QRRK method. On surfaces now, the following reactions take place

Heterogeneous constants have been mainly identified by comparison with particular experimental results.

As can be observed on figure 11, the model calculates the deposition rate as the addition of five heterogeneous reactions, some of which produce silicon, others SiO and the last ones oxidize already deposited silicon. It is particularly significant that the increase in oxygen content of the film, which has been experimentally observed at $\gamma = 0.3$, can be reproduced by the model (see figure 12); such an effect results from the heterogeneous action of water, produced in the gas phase.

Work on this subject is presently going on to improve the chemical mechanism and, hence, the experimental behavior simulation.

9. COLD WALL REACTORS MODELING

The theoretical treatment, then modeling of cold wall reactors appear more difficult to perform than that of hot wall equipments for two main reasons :

- 1 - there does not exist one single dominant geometry of reactor, but a lot of different apparatuses, for epitaxy, for organometallic CVD or for Rapid Thermal CVD for example (see figure 2).
- 2 - the active part of the equipment can no longer be considered as isothermal. On the contrary, very high thermal gradients develop in the reactors, which induce important thermal convective motions. As a consequence, a simultaneous treatment of fluid flow and heat transfer equations becomes mandatory to calculate the velocity and temperature profiles.

Fortunately, as for hot wall reactors, the reactants conversion must be kept low so as to obtain films of convenient uniformity and, as a consequence, the flow and thermal phenomena on one hand and the chemical and mass transport phenomena on the other, can always be treated separately, which simplifies greatly the theoretical approach.

With this hypothesis, several models have been developed, as well by our group in Toulouse [14] as by others ; they always concern simple geometries, often axisymmetrical to remain in two dimensions.

Fig. 11

Fig. 12

As examples, figures 13 and 14 present temperature and concentration profiles corresponding to the particular case of a Rapid Thermal reactor with an idealized geometry ; for simplicity reasons, the case of silicon deposition by silane pyrolysis has been considered.

Fig. 13

Fig. 14

It is important to observe that temperature high values are concentrated at the immediate vicinity of the wafer. As a consequence, silylene forms preferentially in this limited region, moreover with rapid decreases near solid surfaces where this radical is rapidly consumed.

What is interesting to observe is that, due to the small size of the regions where it is formed by pyrolysis, silylene remains at concentrations far weaker than in hot wall reactors. As a consequence, the contribution to deposition of this radical is smaller. Let us observe that this result is in perfect agreement with the initial objective for the development of cold wall apparatuses, which was to limit the homogeneous consumption of reactants before they reach deposition surfaces.

As in hot wall reactors, now, concentrations of less reactive species, such as silane or disilane, appear much more uniform, with only a slow decrease from the entrance to the exit, which demonstrates that the contribution to deposition of these species will be approximately uniform, provided the substrate temperature is maintained constant.

It is time, however, to recall that, in practice, polysilicon deposition by silane pyrolysis is not performed in cold wall reactors, this case being treated here only as an example. In fact, the use of these reactors is limited to operations where homogeneous chemistry plays an important role and, moreover, where gas reactions are so rapid that they cannot be controlled in hot wall equipments.

In such cases, then, the results that have been obtained demonstrate that, with an isothermal substrate and the chamber geometry tested, concentration of the active species produced in the gas phase will not be uniform along the substrate. Without entering in a more detailed discussion, everybody can understand that a reasonable uniformity of deposition rate will be difficult to obtain, either by modifying velocity and temperature profiles by action on the reactor geometry or by adjusting the substrate heating to obtain a convenient surface temperature distribution. Here is the central problem of cold wall reactors, which limits their productivity and, hence, increases the corresponding production cost.

10. MODELING AND SIMULATION INTEREST AND LIMITS

Once a model has been created, it becomes possible to replace a great part of the experiments which were previously necessary by simulation, to improve deposition equipments and procedures.

For example, in the difficult case of phosphorus *in situ* doped silicon thin films elaboration, why not use models and simulation to determine the best tube diameter to wafer diameter ratio to decrease overthicknesses at the wafers periphery or to select pressure values so as to obtain high enough deposition rates ? Why not develop a theoretical study of the entrance region, where silylene and disilane form, so as to adjust the corresponding length to introduce specific control devices ? Our group is presently working on these subjects and several others, but results are not yet clear enough for presentation.

Economic optimization becomes also possible. First attempts in this direction have been made in Toulouse in the simplest case of silicon deposit from silane in a horizontal hot wall tubular reactor. The perfect stages model, presented in section 3, has been coupled with a program to evaluate costs then with a minimization algorithm to determine the economic optimum operating conditions [15].

The most important results provided by such an analysis can be summarized as follows :

- as long as the reactor has not reached its maximum production, the influences on costs of temperature, pressure and gas flow-rate remain relatively weak. As a consequence, the values of these parameters can be chosen mainly to obtain adequate film properties,

- on the contrary, the influences on costs of the number of wafers per batch and of the number of batches per day (that is to say of the daily production) are tremendous, as can be seen on figure 15. From a low production to a high production, costs can be divided by 7, this result coming from the fact that the main contribution to price is the investment amortization.

Fig. 15

This suggests that industrial companies must always operate their production facilities as close as possible of their maximum performances, otherwise their production costs will climb.

For researchers, this suggests that a maximum of efforts must be devoted to increase the productivity of equipments.

If the interest of modeling and simulation appears now clearly, the limits are also well known. They result from the fact that, today, theoretical approaches seem completely unable to provide any interesting information on the deposited thin films quality, that is to say on their structure and, hence, on their properties.

Indeed, modeling can be of help to interpret properties variations experimentally observed ; our group has obtained interesting results by coupling experiments and modeling to analyze differences between silicon films structures deposited from silane and disilane. But, at present and probably for a long time, no predictive theoretical methods are available.

That is to say that, even if a very detailed numerical analysis has been performed, a complementary experimental campaign will always be mandatory to adjust film quality and properties to customers specifications.

11. A FEW WORDS ON EXPERIMENTS POSSIBLE INTERESTING ORGANIZATIONS

As has just been said, experiments are necessary to adjust the quality criteria.

Let me add that, even if significant efforts have been made in research laboratories, only a limited number of CVD operations can be completely analyzed theoretically, particularly by lack of informations on chemical mechanisms or of kinetical data. Again, experiments seem unavoidable.

Then, how to organize the obligatory corresponding campaigns to obtain the best results possible at the lowest cost ?

First, let me recall that a complete procedure of development of a new CVD operation necessarily starts with experiments, at the laboratory scale, to demonstrate the deposition feasibility. Indeed, it is mandatory to examine whether the desired films can be elaborated in a large enough range of operating conditions or not.

The problem is that laboratory reactors are, very often, of the cold wall type and of small size, which minimizes the influence of gas phase phenomena. On the contrary, industrial equipments are mainly of the hot wall type and of large size, which emphasizes the flow and homogenous chemistry influences. The consequence is that the conclusions reached at the laboratory scale are never completely significant for industrial reactors.

A second important problem has already been suggested : in today reactors, quality and productivity cannot be treated independently. This has clearly been put in evidence for hot wall tubular equipments, in a preceding paragraph. For these reactors a compromise has to be found, for the number of wafers, between productivity which asks for the largest number possible and quality which degrades simultaneously. Of course, such a compromise can be determined only by experiments on the industrial reactor itself. The corresponding campaign, with a large scale equipment, is necessarily long and expensive.

The situation appears completely different with the annular reactor which has been previously described, in section 4 and in which quality and productivity can be treated independently. What is then particularly interesting is that the annular reactor can be easily scaled down to a representative fraction that we call a sector pilot plant, and which is simply a small angle of the full scale equipment containing, at least, two wafers to determine an interwafers volume (see figure 16).

Convenient operating conditions can then be experimentally looked after using this sector equipment, with low investment and operating costs.

The very important point is that, as soon as convenient conditions have been found, the industrial mass production can be immediately organized, just by scaling up from the sector pilot equipment to the full 360° annular reactor.

Then, our suggestions for all complex CVD operations, when a theoretical treatment is not possible, are to shorten the laboratory campaign, then, as soon as feasibility has been observed to start an experimental development work with a pilot plant equipment representative of the full scale future production reactor ; it could be the sector reactor previously described or any other apparatus offering the same advantages for scale up.

Fig.16

I want to precise that no guarantee can be given that such an experimental research with the sector reactor or any other pilot plant equipment will be successful, but the uncertainty is not more important than with any other reactor, either of the hot or cold wall type. The fundamental difference is that every time a success will have been obtained, mass production will be immediately insured, without any additional development work. I let everybody estimate the industrial and economic consequences if some of the CVD operations which are still difficult at present -like epitaxy or metal-organic CVD- could be developed in a sector reactor then exploited with the high productivity of a large annular equipment, say with 150 or 200 wafers per batch, for example.

12. TO CONCLUDE

A large number of subjects have been discussed in this presentation, to try to describe the present state of the art in CVD engineering but, also, to suggest possible future advances. Probably as many other subjects have not been treated, such as deposition on already etched surfaces (step coverage) or plasma or laser activation, or metals deposition, etc...

Nevertheless, what could be a general feeling for CVD future ?

My opinion, progressively built by reading specialized journals or participating to conferences like this one, results from two contradictory observations.

The first one is that feasibility of a great number of CVD operations has been demonstrated at the laboratory scale. Moreover, a very active research permanently increases this stock of potential applications, suggesting that CVD technical possibilities are very rich.

In contrast, it is curious to observe that the present rate of development of CVD industrial uses, if far from negligible, nevertheless remains moderate. I strongly believe that the main reason to this limited success lies in the relative inefficiency of the corresponding engineering methods and techniques. In fact, mass production, today, rarely reaches sufficient levels of productivity ; in other words, prices remain too high.

I believe that this situation could improve very rapidly in the next few years provided the new scientific possibilities that we have discussed through this paper be conveniently exploited. For this, research should move from a too passive position, in which it observes phenomena and builds models, to a more active or creative one in which it will use models to design more productive equipments and procedures. This effort should be followed by a similar movement by industrial companies, as well reactors manufactures as CVD users, towards these new methods. In such a context, CVD productivity could increase rapidly and, hence, its industrial applications should develop.

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