EARLY HISTORY OF RAPID THERMAL PROCESSING

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FOREWORD

Although it may still be too early to discern clearly the future direction of the Rapid Thermal Processing as a semiconductor manufacturing technology, it does seem to be appropriate to review the past. This is especially important because the first generation of pioneers is gradually leaving and closing their professional career.
The following recollection of events is my personal story. My recollection of events, as any historical review, may be biased. I am positive that for this reason many readers will find my recollection inaccurate. Beside my notes, I have tried to verify and confirm all information included in this article. I interviewed over one hundred persons and my friends involved in early development of RTP. Twelve people from this group claim priority for Rapid Thermal Processing.

It is impossible to list here all persons who helped me in my endeavor to complete the following article. I wish to thank them all.

I dedicate this article to all frustrated, downtrodden, over-worked, and unappreciated RTP process engineers of the world.

RAPID THERMAL PROCESSING

There is no common agreement on the definition of Rapid Thermal Processing. Usually RTP is understood to be:

- Single wafer processing
- Processing with shorter processing times in comparison to conventional batch furnaces
- Processing with fast heating and cooling rates
- Wafer is thermally isolated from processing chamber
- Cold wall and controlled ambient processing
- Processing with control of thermally driven surface reactions

The most important difference between conventional batch thermal processing and Rapid Thermal Processing is the fact that in an RTP system the processed wafer is never in thermal equilibrium with the surrounding environment.
The word “rapid” was used the first time in the Detailed Description section of the Mammels Patent “Method of Heat Treatment of Workpieces” filed in 1968. On a side note, there was a lot of jockeying for semantic position – Varian was pushing the term Isothermal Annealing, and AG Associates pushing “Heat Pulse Annealing”, and academics using terms such as “Blink Furnace Annealing”. As time passed Rapid Thermal Annealing and Rapid Thermal Processing became the common term; a lot better than Rapid Isothermal Processing – whose acronym (RIP) didn’t seem particularly auspicious.
In reality, RTP is one of the most complex segments of semiconductor manufacturing involving the quantum and solid state physics, optics, and engineering. However, the basic

principle is very simple. This simple basic principle of RTP leads many people to believe that any “garage operation” can build an RTP system. There was a time when 14 companies offered rapid thermal processing systems. A lot of people learned the lesson the hard way, many times paying a high price for mistakes made. In such situations it is human nature that people remember the historical development from their point of view.
RTP may be seen as a success or a failure, depending on what you want to see and if you are user or manufacturer of RTP equipment. The reason for many failures of RTP in the past is so called “mind conditioning”. Mind conditioning is basically an addiction by being constantly told that some things are good and others are bad.
Regardless of the past RTP slowly gained acceptance for implant anneals and processes where chamber ambient needs to be well controlled. Very likely, as the trend towards single wafer processing continues, RTP will gradually play a more important role in thermal processing of semiconductors.
There is common belief that Rapid Thermal Processing of semiconductors was a continuation of the laser processing of semiconductors. However, incoherent lamp based systems were developed and used much earlier than laser processing techniques. Unfortunately, several excellent ideas were invented too early when no market and application existed. This is probably the reason why Rapid Thermal Processing of semiconductors instead of going through a thorough and systematic scientific development followed a chaotic and spontaneous road of partial improvements.
In the past the RTP market was so small that it never attracted large companies with resources to solve serious RTP technical challenges. The conventional batch furnace has proven to be a reliable, low cost technology. Traditional lamp based RTP systems still have many problems in a manufacturing environment. As long as a working alternative to the processing is available it is very difficult to significantly penetrate the market with a new unproved technology.

THE BEGINNING: WITHOUT SEMICIONDUCTORS

Frequently, something new is actually something old which has been forgotten.
Many principles of the Rapid Thermal Processing as known today originated in materials science experiments. To understand “annealing” (or the opposite process “quenching”) and its effect on material properties required the controlled heating and cooling of the material sample.
In 1957 the group of scientists at California Institute of Technology in Pasadena designed a solar furnace with parabolic Al reflector [1] which was later on used to heat amorphous silicon layer to temperature 1000 ^{o}C with a heating rate 1000 ^{o}C/sec [2].
The other system, with remarkable resemblance to RTP systems designed twenty years latter, was built by Naval Research Laboratory at the beginning the 60’s. In May 10, 1961 F.J. White presented at 1961 SESA Spring Meeting held in Philadelphia results of a simulation of the conversion of mechanical energy into thermal energy to produce aerodynamic heating. The system is shown in Fig. 1.

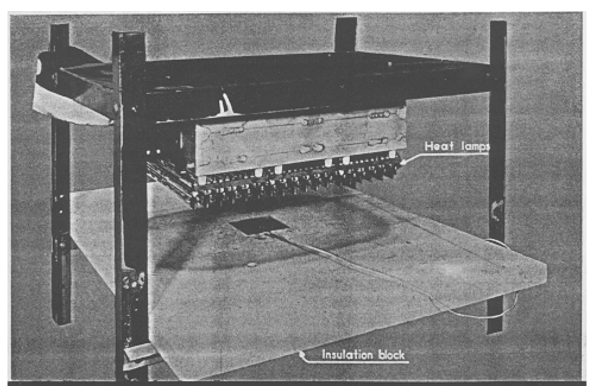


Fig. 1 RTP system used to simulation of the conversion of mechanical energy into thermal energy to produce aerodynamic heating. [F. J. White, 1961]

The tungsten filament quartz lamp (each 1000 W) configuration and reflector configuration is almost identical with reflector design used in RTP systems in the end of the 80’s by many RTP equipment manufacturers.

It is important emphasize that the electrical power delivered to lamps was not controlled. Sample temperature was measured by a thermocouple attached to the sample. As we will discuss later the temperature measurement of the processing sample was and still is the major issue of RTP.

WHEN WAFER WITH DIAMETER 1$^{1/4}$” WAS CALLED “THIN SEMICONDUCTOR SLICE”

In December 2, 1968 Walter K. Mammel of Western Electric Company in New York filed Patent # 3,627.590 titled “Method for Heat Treatment of Workpieces”.

Although young engineers may find the formulation such as ”the thin semiconductor materials are, of course, extremely fragile and must be handled with great delicacy” laughable today, Mammel’s patents define all the requirements of a state-of the-art RTP system.

Mammel’s patent describes two configurations of the system shown in Fig. 2. The fundamental features of both systems include a thermally isolated wafer and wafer rotation. The system used six 2 kW halogen lamps. The typical process described in the patent is phosphorus doping from the gas phase. The processed sample was enclosed in the quartz processing chamber filled with the processing or inert gas. The systems had no capability of measuring sample temperature. The temperature of the sample was controlled by positioning of the sample in the thermal gradient field between the reflector and sample. All lamps run with the same constant power.

The major feature, of the invention, which Mammel recognize, is thermal isolation of the wafer. This feature is one of the main differences between rapid thermal processing and conventional methods. A quartz pin did not support the wafer during processing. Instead the flow of the gas “levitated” the wafer above chuck and separated the big thermal mass of chuck from the “thin semiconductor slice”.

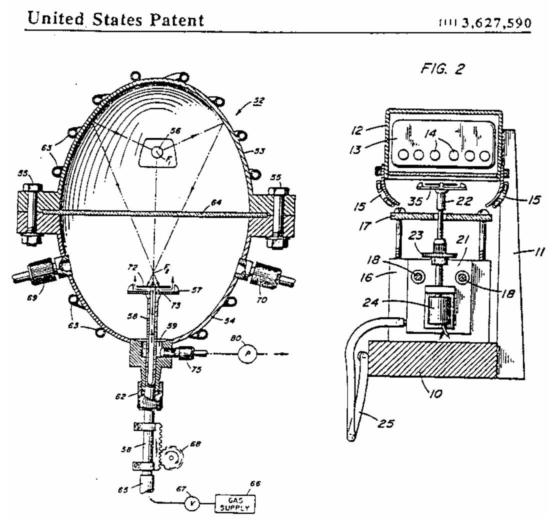


Fig. 2. RTP system designed by Western Electric Company in 1968

In March 3, 1973 V.P. Chabarov and A.N. Beloborodov filed Soviet Union Patent # (11)432216 describing a water-cooled cylindrical reflector with six quartz lamps. The temperature of the sample was monitored by pyrometer and electrical power was controlled closed loop by SCR’s. The processed sample was placed into a quartz chamber filled with processing gas. The configuration of the equipment is shown in Fig. 3.

In July 26, 1973 E.R. Anderson of Applied Materials filed Patent # 3,836.751 “Temperature controlled profiling heater”. The object of the invention is the improved “heater” which includes a plurality of radiant heating elements to provide a desired temperature profile. Another object of the invention includes “means for sensing the temperature produced by the heating elements in different regions and maintaining the temperatures at predetermined levels”.

In October 26, 1976 General Electric in Schenectady filed patent (#4,101.759) describing “semiconductor body heater”. The basic configuration is shown in Fig. 5. The system was designed for temperature gradient zone melting. This patent for the first time discussed the temperature non-uniformity across wafer as a result of non-uniform irradiation. Experimental data shows that the temperature across wafer may vary by as much as 40 ^{o}C over distance as small as 10 mm. The invention solves the problem of temperature non-uniformity by independently controlled power to each lamp.

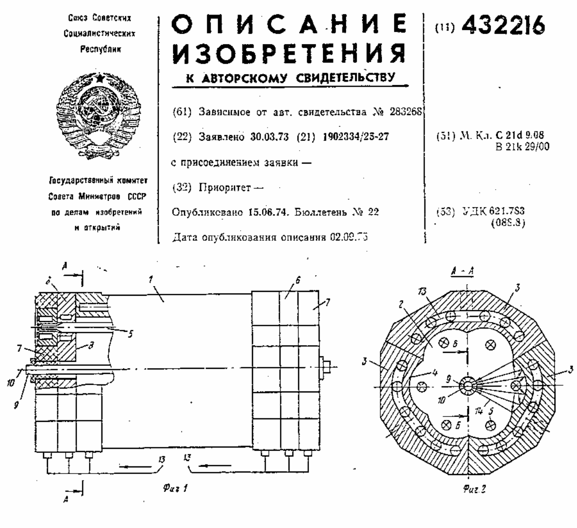


Fig. 3. RTP system with cylindrical reflector system [Soviet Union, 1973]

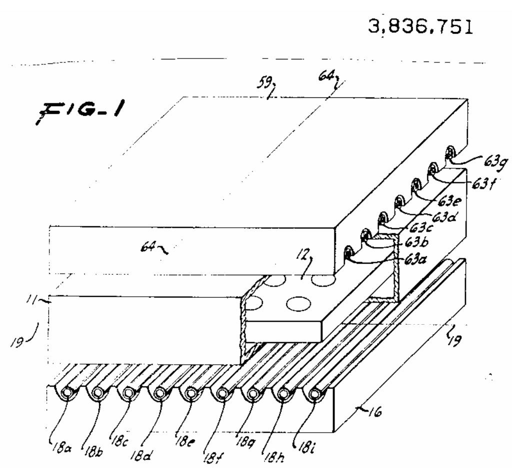


Fig. 4. Applied Materials radiation chamber [Anderson 1973]

In the mid 70’s the only company manufacturing and marketing “a radiant heater” was Research Inc., in Minneapolis. They were marketing a flat radiant heater, which employed a planar array of tungsten filament quartz lamps. The system was using 6 lamps in array approximately 40x8 cm.

Although reasonable RTP equipment were available at the beginning of the seventies, the young semiconductor industry had no need to consider Rapid Thermal Processing, and only material science engineering pushed RTP development. At this time the 3” wafer diameter was state-of-the-art, gate length was around 10 μm and junction depth approximately 1.6 – 2 μm. Intel’s latest chip in 1974 contained 6000 transistors. The newly introduced 1kbit SRAM with a complete CMOS structure (L = 8 μm) was an unusual design at that time when NMOS and bipolar technologies dominated processing.

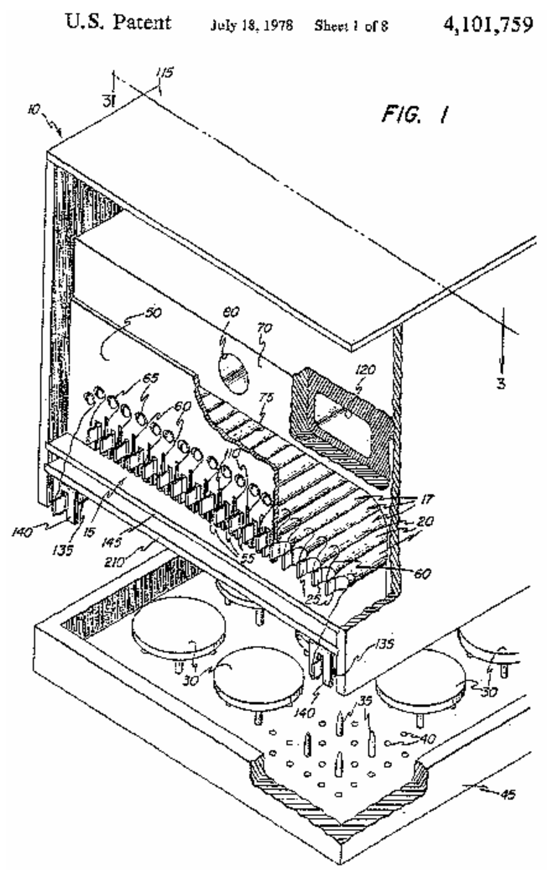


Fig. 5. General Electric RTP system designed in 1976

LASER ANNEALING

In beginning of 60’s several groups of researcher in Soviet Union and USA investigated the physical properties of semiconductor during irradiation by laser beam [3], [4], [5], [6], [7].

Most of the experimental work was focused on the characterization of the optical properties and recombination in strongly excited silicon with ruby laser (λ=0.66 and 1.06 μm). Blinov noticed that the mechanism of the increase of reflectivity from the surface in a strongly excited semiconductor exhibits an unusual behavior and suggested that such behavior may be explained by metallization of a thin surface layer by melting.

In October 18, 1968 G.H. Schwuttke, J.K. Howard, and R.P. Ross of IBM filed Patent 3,585.088 “Method of producing single crystals on supporting substrates”. The motivation behind this invention was “to eliminate the conventional starting wafers in the manufacturing of solid state devices”. In accordance with this invention, a film of crystalline material is deposited upon a suitable substrate (glass polycrystaline substrate or graphite). A portion of the film is irradiated with a laser beam pulse having intensity sufficient to re-orient the crystalline lattice of the film. Modification of this method was used to produce P-N junction diode (see Fig. 6). An amorphous silicon layer was deposited on silicon substrate.

The layer was coated with thin phosphorus layer. The sample was then irradiated by ruby

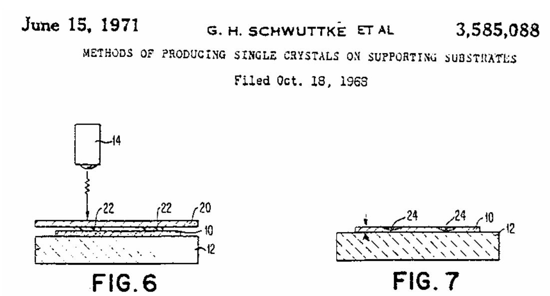


Fig. 6. P-N Junction Diode produced by laser annealing [IBM in 1968]

laser and amorphous layer recrystalized. The electrical performance of the diode is described in paper [8].

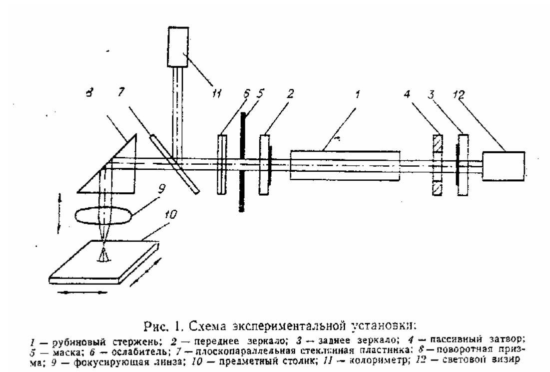


Fig. 6 Laser system used by Kutolin and Kompanec to form P-N junction diode. [Soviet Union 1969]

Kutolin and Kompanec described a very similar experiment in paper [9]. An experimental setup used in their work is shown in Fig. 6 and an I-V characteristic of diode formed by diffusion from solid phase is shown in Fig. 7.

It is important to recognize that in both experiments no ion-implantation and no sophisticated photolithography technique have been used. The area of the diode was defined by laser beam diameter. Such works demonstrate feasibility of the laser for thermal processing. However, they did not involve the annealing of implanted layers.

In April 29, 1974 Philipovich group submitted a paper [10] suggesting for the first time laser annealing of ion-implanted layers.

That same year a group of Prof. Khaibullin at University Kazan demonstrated feasibility of the laser annealing of implanted layers [11]. They used heavy dose Phosphorus implant annealed by laser. Reference anneal was performed in furnace at 800 ^{o}C for 30 min. Example of their data is shown in Fig. 8. An experimental setup used by Khaibullin group is shown in Fig. 9.

In July 1977 at the First U.S.-USSR Seminar on Ion Implantation held in Albany, NY two Russian research groups impressed audience with their work on laser annealing of implanted layers.

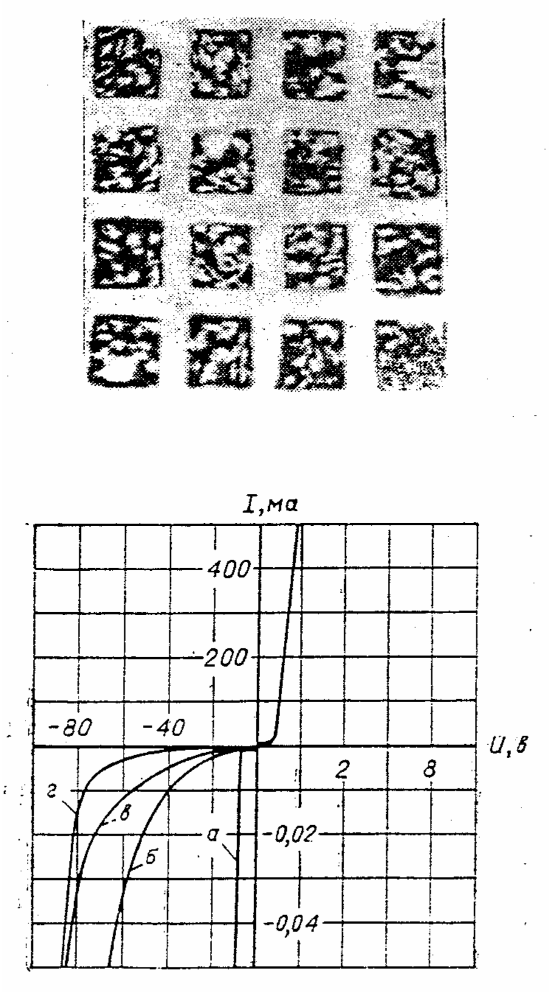


Fig. 7. P-N Junction Diode produced by diffusion from solid phase and laser annealing [Soviet Union 1971]

A.V. Dvurechensky of Institute of Semiconductor Physics of Academy of Sciences of the USSR in Novosibirsk and his co-workers found that the redistribution of impurities in Si occurs after annealing with both millisecond and nanosecond laser pulses. The character of redistribution depends on the power density of the light beam. They suggested that at high power densities the redistribution of impurities is caused by the flux of excess vacancies or by the recrystalization of the melted surface layer. Prof. I.B. Khaibullin and his group from Kazan Physical Institute of Academy of Sciences of the USSR described the reordering of the disordered implanted Si layers after laser pulse annealing. Khaibullin suggested for the first time that the mechanism of laser annealing couldn't be reduced to simply a heating effect. They concluded: "some additional process couldn't be reduced to simply a heating effect.

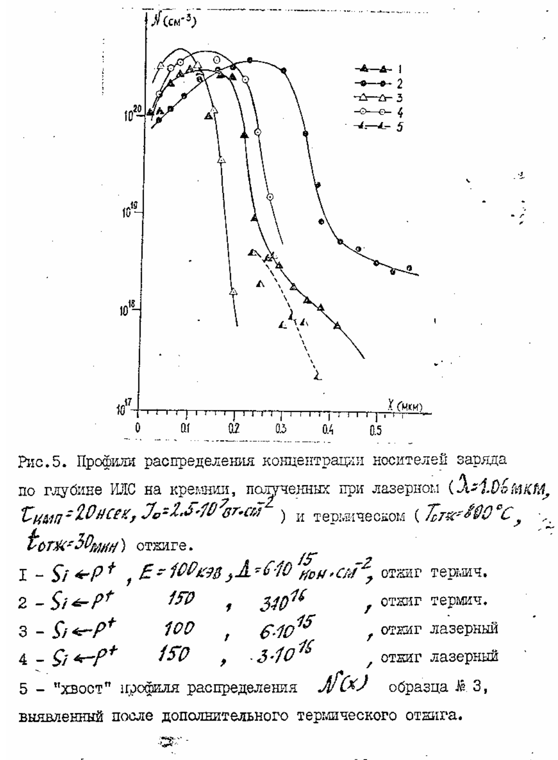


Fig. 8. Implanted profiles after laser annealing [Khaibullin 1974]

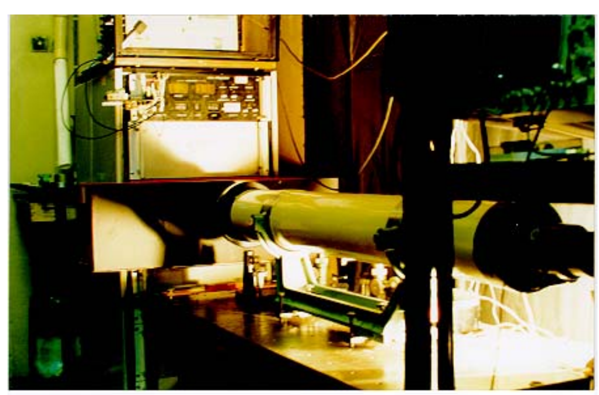


Fig. 9. Laser annealing experimental setup used by Khaibullin group

They concluded: "some additional process stimulating the effective recrystalization of disordered implanted layer and the electrical activation of implants should be taken into account".

The pioneering work of Kazan and Novosibirsk groups trigger incredible interest in the scientific community.

Bell Laboratories group: John Poate, George Celler, Harry Leamy, Walter Brown, was probably the first U.S. group who systematically followed work on laser annealing of implanted layer. They developed in 1978 a thermal melting model of laser annealing of implanted layers. Based on the measurement of redistribution of As during Q-switched laser annealing they concluded that solid phase diffusivity could not account for measured redistribution of As. The thermal melting model has been identified as a simple unifying basis by which a large body of experimental results from pulsed excitation could be understood.

Sometime in 1979 Naval Research Laboratory explored interaction of the laser radiation with semiconductors. The project was initially motivated by the need to account for some laser damage experiments for infrared detector materials such as InSb and HgCdTe.

Jerry Meyer with Fil Bartoli, Mel Kruer, Roger Allen, Leon Esterowitz, and later Craig Hoffman worked out the theoretical formalism of laser beam interaction with semiconductors that appears in the February 1980 issue of Physical Review B. The formalism was able to account for some previously unexplained trends in the InSb data, and was confident enough of its generality that it made sense to go ahead and apply it to other semiconductors and other wavelength regimes as well. That led to the second paper, treating laser damage thresholds in Ge, Si, and GaAs in addition to InSb [12]. NRL group latter did some analysis of laser annealing in crystalline and amorphous silicon, but didn't push that very far after presenting the results at an international conference in Mons, Belgium.

Richard Wood, C.W. White, R.T. Young, and G. Jellison, Jr. from Solid State Division of Oak Ridge National Laboratory in the early 80's ran research on "pulsed laser processing of semiconductors" Volume 23 in the Willardson and Beer Series on Semiconductor and Semimetals, is based largely on the ORNL work. On page 30 they make a few comments about RTA and mentioned that it was apparently inspired by the laser annealing work. In fact, they made solar cells out of some of the material early annealed by laser with quite disappointed results. At that time they concluded that RTA was not very promising for minority carrier devices but should work well for majority carrier applications.

The measurement of the complex dielectric function of Si at elevated temperature performed by Jellison was especially important in determining how laser radiation couples to electronic and vibrational states of the system.

While Bell Labs, NRL, ORNL and other research groups (Hughes, University of Rome) concentrated on the application of pulse laser annealing, Stanford University focused primarily on the use of scanned CW laser for annealing of implanted layers. In 1979 Prof. J. Gibbons presented at 11th Conference on Solid State Devices in Tokyo the paper "Application of scanning CW laser and electron beams in Si technology". The principal results obtained from this work may be summarized as the following:

- For thin amorphous layers of Si, the annealing process is a solid phase epitaxial regrowth
- No diffusion of implanted impurities occurs during annealing, irrespective of whether the amorphous layer is created by ion implantation
- The electrical activation can be 100% even for the impurity concentrations that exceed the solid solubility limit

Stanford group, which call itself "Stanford Annealing Mafia" first recognized that "high controllable process for heating of surface of a semiconductor may leads to the development of number of other processing steps, namely growth of oxides, and silicides.

In period of time 1978 and 1983 Van Vechten published a series of works with unconventional interpretation of laser annealing processes. Honest and idealistic Van Vechten, in search of truth realized that several physical phenomena of laser annealing couldn't be explained by thermal melting model. Van Vechten and his colleagues noted evidence of athermal component of laser annealing and proposed Plasma Annealing Model [13]. Proponents of the plasma annealing model assert that high concentrations of excited carriers, which occupy antibonding orbitals, are softening the lattice.

Electron-hole pair formation and excitation of free carriers are the two major absorption mechanism in Si irradiated with visible and near-infrared radiation. The excess energy of the electronic gas is rapidly transferred to the lattice vibrations, increasing the crystal temperature. Energy conservation requires that the energy of the absorbed photons will be emitted by luminescence or dissipated as heat. No one is questioning this basic fact, the main source of the controversy is the rate of the energy loss to the lattice. Proponents of the thermal melting models claim that energy transfer takes < 10^{-10} sec, while the plasma annealing model considers longer energy transfer.

The controversy fueled by "mind conditioning" and politics deeply divides the scientific community and differences are still not settled.

Looking back today we know that basically both camp were partially right – melting may occurs (and may occurs at lower temperature than classical melting), and state-of-art RTP annealing works show that there is athermal component of annealing even at much lower concentrations of free carriers.

Many laser annealing experiments, especially earlier works, are just examples of very poor experimental practice where uncertainty and speculations are so big that no reasonable conclusion regarding sample temperature can be made. In the vast majority of laser annealing experiments the sample temperature is not controlled and properties of annealing material used are not characterized. On the other hand, good laser annealing work analyze in great detail physical processes involved in transfer of photon energy to the crystal lattice. Absorption and recombination processes and optical properties of semiconductors such are reflectivity, emissivity, thin film interference, etc. are now much more understood.

The other characteristic feature of the majority of laser experiments is that the semiconductor sample was not placed in any type of processing chamber – the key requirement of high volume, high yield of semiconductor manufacturing. This was very quickly recognized as a major disadvantage and after an initial peak of enthusiasm the effort at IBM to use laser processing as a tool to produce 3-D circuit structure was terminated. As the time passed, it was clear that laser annealing would be not incorporated into industrial production. A decade later there was second hope for laser annealing when Japanese company MIWA introduced the excimer laser annealing system with beam homogenizer. The assumption was that the annealing system may work in a similar fashion to a stepper by annealing one frame of die at a time (so called Projection Annealing). In Fig. 10 is shown a typical example of annealing "stamps" which the author performed with MIWA system. Serious manufacturing and integration issues lead to discontinuing of the system after first series of tests.

Around 1980 Spire Corporation demonstrated the capability of Pulse Electron Beam Annealing for ion implanted layers. Spire introduced the SPI-PULSE 7000 Pulsed Electron Beam Processor (Fig. 11) with vacuum loadlock and wafer transport mechanism. The system was design to produce 10 MW of solar cell per years. Beside ion implant annealing applications, system was targeting metal contact sintering and fast quench annealing applications. The system delivered 500 J of energy per pulse, which was sufficient to melt a very large surface area not only of semiconductors, but also the metals. The Spire solar cell program was terminated as oil price decreased. Since that time nobody re-visited electron beam annealing.

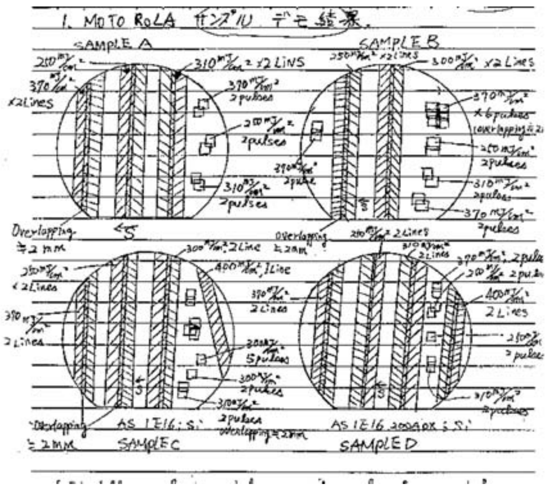


Fig. 10 Laser Projection Annealing (MIWA Corporation XeCl Laser with beam homogenizer) [Lojek 1990]

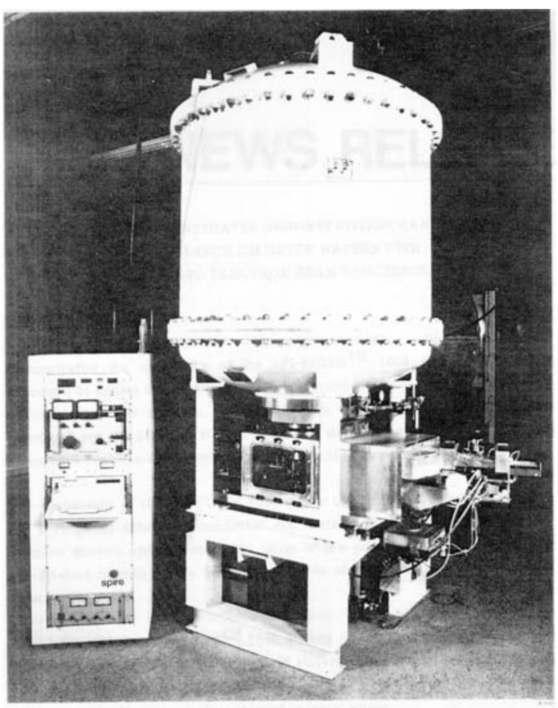


Fig. 11. Spire Corporation SPI-PULSE 7000 Pulsed Electron Beam Processor [1980]

Perhaps it is somewhat ironical that laser annealing, which received such an enormous amount of attention at the time did not result in any practical industrial application. An even more surprising fact is that engineers working later on RTP development did not learn too much from the physicist working on laser annealing. For example, concentration and wavelength dependent absorption or non-constant emissivity of Si have been completely ignored for a long time by RTP community.

THE RTP PIONEERS

At the beginning of 1979 Ron Fulks (who latter went to Xerox PARC) and Tom Yep (who later become a VP at Lam Research) were working on the Varian rapid annealing project. Ron Powel joined the group in September 1979. Varian's interest was to use RTA for annealing implanted layers. The project split into two parts: rapid heating of wafers using a rastered, narrow E-beam (Tom Yep's) project), and rapid heating with a focused xenon arc lamp produced by Eimac division of Varian in San Carlos. Ron Powell and Howard Gilliland abandoned the "strip illumination" (used latter by Arnon Gat again) and decided that large area irradiation of the wafer was a better idea. They used a 6 kW wide-beam, mechanically shuttered Xenon arc light from Optical Radiation Corporation (the same one which was used in projection equipment in drive-in movie theater) which produced uniform irradiation of circles comparable to 3 and 4-inch wafers. The center to edge thickness of the graphite heater could be designed in such way that an extremely uniform radiation field may be produced at the wafer – or one that gave greater edge illumination for on-wafer temperature uniformity. The system worked quite well and Varian Extrion division liked the idea of a cheap, graphite-meander heater which could be retrofitted onto an automated DF-4 implanter endstation.

Ron Fulks at Varian and Carl Russo at Extrion drove the project towards production. The result was the Extrion IA-200 introduced at Semicon-West in May 1981 (see Fig. 12). IA stands for Isothermal Annealer and 200 referred to the fact that the mechanical limit of

"WayFlow" wafer transport mechanism was 200 wph.
There are a few important points to be made about the IA-200. First of all, this was the first commercially available RTP annealing system using incoherent radiation corresponding to the black body temperature approximately 1450 ^{o}C. Varian system provided fully automated equipment for the technology which was not yet developed.
The system had limitations in control and had to be run in vacuum to protect the heater. It also was hard on wafers and a broken wafer took many hours to clean.

Fig. 12. Varian Extrion IA-200 RTP system introduced at Semicon-West in May 1981

Despite the optimistic prediction of Bill Bottoms, general manager of the Extrion division during Semicon West, about the new way of annealing implanted wafers, it was very soon clear, that the IA-200 is not going to be a commercial success. Looking back probably the mistake was the fact that Varian targeted only implant anneal applications.
At the end of 1980 George Celler and Lee Trimble of Bell laboratories at Murray Hill designed a RTP system used for recrystalization of polysilicon layers over oxide (so called LEGO process).

Fig. 13. Lee Trimble and George Celler at the front of RTP system designed at Bell Labs in 1980.

The system, shown in Fig. 13 was using water cooled reflector with air cooled array of tungsten quartz lamps positioned under the processing chamber. Electrical power was controlled by HP computer through SCR's. A pyrometer sensed the temperature of thermally isolated wafers through a quartz window. The same system was also used later for annealing of SIMOX silicon-on-insulator wafers.

Approximately at the same time on the West coast fresh Stanford University graduate, Arnon Gat, while consulting for Coherent Corporation started to construct a lamp scanning apparatus for annealing of implanted wafers. A sewing machine motor was used to turn a simple lead screw onto which a semi-circular reflector was mounted (Fig. 14). The high pressure water cooled arc lamp was placed at the center of reflector. World War II variacs were used to drive the lamp. Because the wafer was placed on the resistive heater chuck, the lamp power was not sufficient to anneal implanted silicon. Scanning of the lamp along the wafer also resulted in severe thermal stress, degrading the flatness of wafer.

G.Fuse, K. Kugimiya and K. Inoue of Matsushita described at 41th Meeting of Japanese Society of Applied Physics in 1980 "Blink Furnace". The 2" wafer was placed between two 3" wafers heated by SiC rod elements. The principle was basically the same as Hot Plate or HotLiner introduced later.

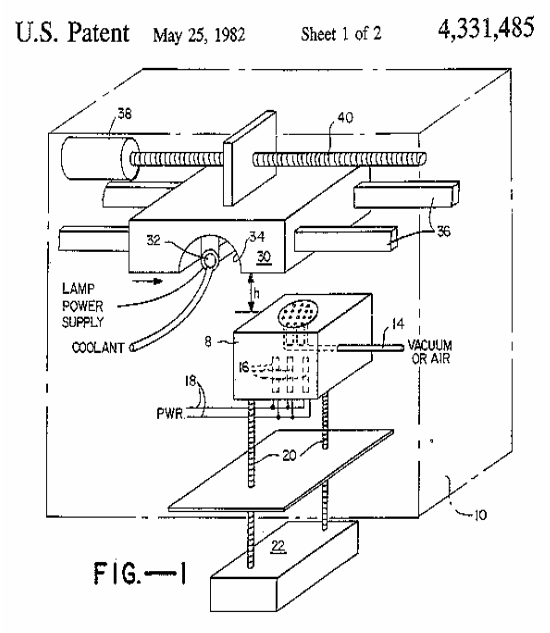
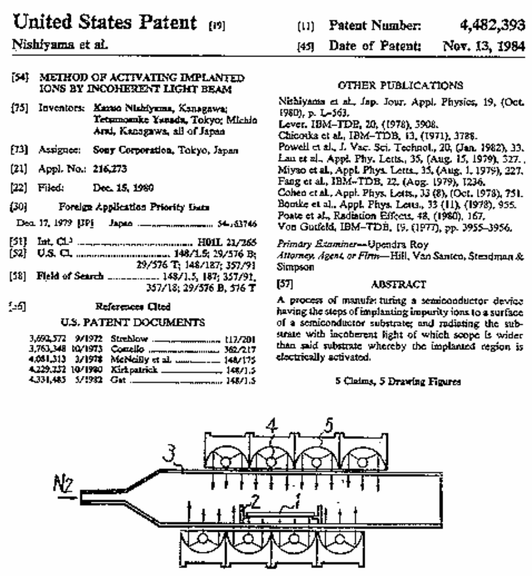


Fig. 14. Arnon Gat's lamp scanning apparatus for annealing of implanted layers

In December 15, 1980 K. Nishiyama, T. Yanada, and M. Arai of SONY filed patent application 4,482,393 "Method of activating implanted ions by incoherent light beam" (Fig. 15). The invention has been published in October 1980 issue of Japan Journal of Applied Physics. [14]. Although the patent does not say anything about the wafer temperature measurement the configuration of system as described in the patent defined trend in RTP equipment as used at the beginning of 80's: quartz wafer support inside the rectangular chamber with tungsten filament quartz lamps located above and below of the quartz tube.

Authors described the RTA process as used today. In experimental part of the patent they showed dependence of the sheet resistance on the annealing time for boron implant into N-type silicon and compare resistance with furnace annealed sample. SONY claims as invention the following:

- "According to the furnace annealing at 1100 °C for 15 min, it will be understood that, according to the above example of the invention a semiconductor wafer having the characteristic similar to that of the prior art can be produced by radiation of light for about 6 seconds".
- "A process of manufacturing of a semiconductor device comprising the steps of: a) implanting impurity ions in a surface of a semiconductor substrate, and b) radiating continuously with a plurality of incoherent lights emitted from a heated refractory metal and having a wave length of 0.4 – 4 μm and with beam wider than said substrate, the intensity of said light beam such that the implanted region is annealed so as to be electrically activated.


United States Patent [19]
Nishiyama et al.

[11] Patent Number: 4,482,393
[45] Date of Patent: Nov. 13, 1984

[54] METHOD OF ACTIVATING IMPLANTED IONS BY INCOHERENT LIGHT BEAM

[75] Inventors: Kazuo Nishiyama, Kanagawa; Tetsunosuke Yanada, Tokyo; Michio Arai, Kanagawa, all of Japan

[73] Assignee: Sony Corporation, Tokyo, Japan

[21] Appl. No.: 216,273

[22] Filed: Dec. 15, 1980

[30] Foreign Application Priority Data

Dec. 17, 1979 [JP] Japan 54-163746

[51] Int. Cl.³ H01L 21/265
[52] U.S. Cl. .... 148/1.5; 29/576 B; 29/576 T; 148/187; 357/91
[58] Field of Search .... 148/1.5, 187; 357/91, 357/18; 29/576 B, 576 T

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Primary Examiner—Upendra Roy
Attorney, Agent, or Firm—Hill, Van Santen, Steadman & Simpson

[57] ABSTRACT

A process of manufacturing a semiconductor device having the steps of implanting impurity ions to a surface of a semiconductor substrate and radiating the substrate with incoherent light of which scope is wider than said substrate whereby the implanted region is electrically activated.

5 Claims, 5 Drawing Figures

Fig. 15. SONY Patent describing RTA equipment and RTA process [1980].

In April 1981 a group of scientists from former Soviet Union and East Germany published the paper "Flash lamp annealing of As implanted silicon" [15]. They used flash annealing equipment with Xe gas-discharged lamps generating 10 msec pulses with average wavelength 0.5 μm. The energy density of the pulse varied between 50-85 J/cm^2. The authors concluded that "incoherent light pulses represents a practical approach to cover large areas uniformly with throughout the whole volume, however, it will be advantageous to irradiate the back side of the wafer".

In late 1980 AVCO Everett Research Labs (now part of Textron) had done some work on the heating of silicon. They developed high frequency (50kHz) vortek stabilized arc lamp for laser pumping. AVCO lamp was not very reliable. Bert Plurd of AVCO contacted Vortek Industries in Vancouver and they ran several evolutions with Dave Camm's Vortek lamp. Due to the changing business in AVCO they decided to terminate the project and they tried to sell the idea to Varian. However, Varian was finishing their IA-200 and evidently was not interested. AVCO's Alan Kirkparick and Peter Rose approached Eaton. After some discussion, Eaton concluded that a high power incoherent light source might have some promise and they introduced Eaton to Vortek. In mid 1981, Eaton decided to hire Jeff Gelpey who become project manager for "Rapid-Optical-Annealing Products". A simple manually loaded system was designed and built with a Vortek lamp and was running in a demo lab at Eaton late that year. The Vortek lamp (Fig. 16) was originally designed for outdoor lighting and it was not particularly suited for semiconductor industry. Lamp was large, required a great deal of power and ancillary equipment, and it was very loud. In spite of these problems, the system worked and Eaton

Fig. 16. VORTEK arc lamp delivering 20 kW over 40 cm^2

went on to design an automated system introduced at Semicon West in 1983.

Eaton named the system NOVA ROA-400 (Rapid Optical Annealer). The system employed full automatic casette-to-casette wafer transport, fully automated feedback control with an optical pyrometer. Water cooled process chamber was completely separated from lamp reflector by a quartz window. Contrary to Varian Eaton was marketing the system for annealing application, contact alloying and silicide processes. At that time no PC based controls were used. The industry standard was Fluke 1722A controller with touch sensitive CRT.

Eaton sold several systems, however, as competitive systems gathered more market share, it was apparent that the Eaton/Vortek design was impractical. Jeff Gelpey left to Peak Systems and Eaton exited the market in 1988.

In October 1981 Arnon Gat formed AG Associates and abandoned the scanning lamp. Arnon designed in his girlfriend Anita's living room, "RTP breadboard" RTP system (Fig. 17.). After demonstration that silicon may be heated, Arnon approached Thermco and Eaton, being previously turned down by Coherent. Both furnace manufacturers were not convinced enough and as time passed by, it

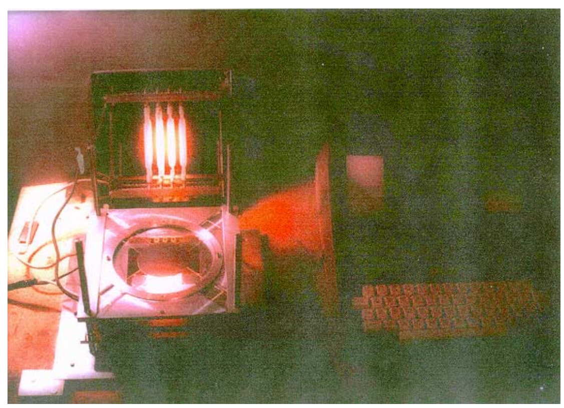


Fig. 17. RTP system designed in Gat's living room.

become clear that none was interested. With time running out, Arnon redesigned the breadboard, increased the number of lamps and replaced short lamps with a long one and in

matter of month was ready for the first annealing experiment. No temperature measurement, no processing chamber – just an on-off system. The system was packed and named Heatpulse 210 M. Arnon mailed postcards to the numerous process engineers before Semicon West in 1981, urging them to "bring the wafer to Semicon show and while waiting he will anneal wafer" (Fig. 18). The 210 M system had a price tag of $ 27,300.00 and the first unit was sold to Motorola. However, the semiconductor industry converted to 4" wafer diameter and started to scale down below 2 μm and particle contamination become issue.

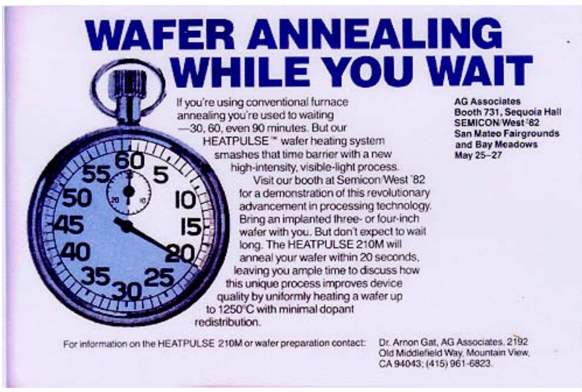


Fig. 18. Arnon Gat's postcard distributed before Semicon West 1981

Stanford professor Dick Swanson suggested to Arnon to place wafer inside quartz chamber. Arnon contacted quartz shop and requested some quartz work. Arnon had been told by Heraeus Amersil salesperson that his job is no problem and promised future contact by Howard Young, who was at that time a machining expert at Heraeus. When the salesperson asked Howard what he thought about job, Howard said: "Absolutely no way. Tell him to forget it, the job looks like a big pain". I can't, said the salesperson, I told him we could do it with no problem and that you would be calling him next week. So, Howard visited a "garage shop" on Middlefield Rd. in Mt. View. During the first visit Arnon showed to Howard a glass funnel which was cracked.

Arnon: Can you fix this?

Howard: Where does this go in your RTP machine?

Arnon: It doesn't, it's part of my girlfriend coffee express machine she got from Japan. Can you repair it?

Howard: Sure, no problem, in fact I'll do it at no charge.

Upon returning to quartz shop Howard asked a technician "Can you fix this?" No way, this is Pyrex. We are a quartz shop.

Turnabout being fair play, Haraeus ended up making a brand new piece out of quartz, thereby making Anita the owner of the most expensive coffee maker in the land.

Heatpulse 210M was retrofitted with a quartz tube and rotometer. The price was updated to $ 33,300.00 and the Heatpulse 210T (Tube) was born. Because the system was small, inexpensive, and easy to operate, it became very successful. During its lifetime AG Associates sold approximately 240 manual 210T systems mostly to the research community.

Heatpulse 210T was gradually improved. The later systems include temperature monitoring using small "witness sample" with embedded thermocouple. A key person who contributed to the development of 210 T was Steve Shatas – a brilliant engineer and after he left AG, very unsuccessful businessman.

In mid 1982, Avid Kamgar and E. Labate of Bell Laboratories designed an RTP system for zone melting [16]. The wafer was held in a rectangular quartz chamber purged by Argon. Six high intensity tungsten filament lamps heated the wafer from the bottom. A line heater on the top with additional tungsten filament lamps placed in elliptical reflector focused on a narrow strip. The line heater was scanned across the wafer by a motor at the desired speed, to help the molten zone traverse the surface of the wafer. A photograph of the system is presented in Fig. 20. The same system was used for many other pioneering RTP works at Bell labs. Sometime during 1983, in this system, Avid Kagmar ran the first nitrided oxides with ammonia and opened a new application to RTP processing.

TIME OF OPPORTUNITIES

Between 1984 and 1985 other RTP systems were introduced. RTP market was estimated to be $ 10–15 million. At that time semiconductor

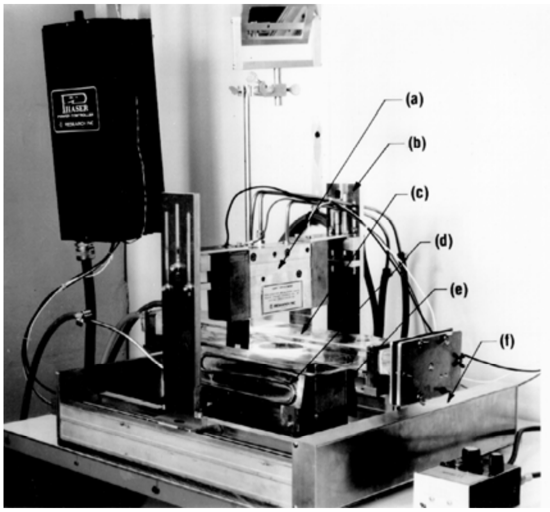


Fig. 20. Bell Laboratories designed RTP system for zone melting [Kagmar1982]

manufacturers do not asked for a cost of ownership analysis and 98% uptime. The industry still had a tendency to work with small or new businesses if the technical idea behind product may result in better processing performance.

In the U.S., Eaton, Peak Systems, Tamarack, Nanosil, AET-Thermal, and Process Product emerged as new RTP vendors following the AG Associates and Varian. In the Pacific Rim, several Japanese vendors (Kokusai, DaiNippon Screen, ULVAC, and Koyo-Lindberg) sold systems mostly to the Japanese market. There was an attempt to market the Kokusai system in U.S by Veeco, but no system was sold. In France AET – Addax, and Sitessa also introduced a series of custom and standard RTP products.

In 1983, Tim Stultz (Fig. 21) founded Peak System Inc. in Fremont In 1987 Peak had about 40 employees and introduced the first product called ALP 6000. Based on Stultz's work at Stanford University the system, employed a single energy source – arc gas discharge lamp. The lamp was called in Peak's marketing literature "Silicon Specific" (Fig. 22) because 95 % of its spectral output has wavelength shorter than 1 μm. The lamp spectral output, equivalent 7500 ^{o}K blackbody radiator, eliminates dependence on free-carrier absorption.

Fig. 21. Peak Systems Inc. founders: Tim Stultz (in center), McKnight (right), and financial officer Neumann.

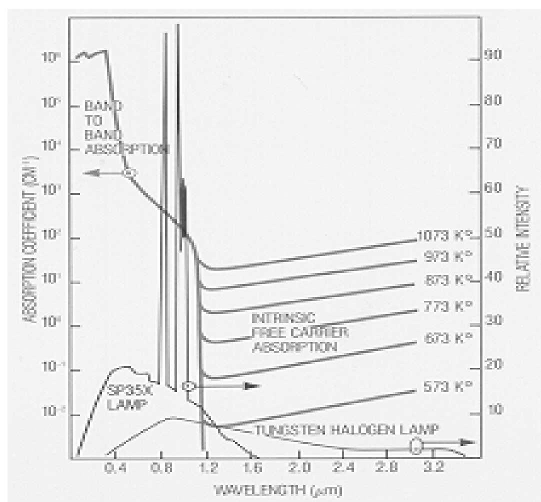


Fig. 22. Radiation spectrum of Peak Systems "Silicon Specific" arc lamp

The concept used in ALP 6000 was in many ways revolutionary. 8086 PC controlled system with software superior to any other competitor

The system ran under real-time process control with closed loop. User may calibrate the pyrometer against K type thermocouple. A cold wall chamber was constructed of polished steel as a vacuum chamber. The sealed quartz window at the top of the chamber separate wafer from the water cooled lamp and reflector assembly.

The Peak had a good deal of success in competing with AG associates for fully automated systems in the late of 80's.

In 1984 AG Associates introduced Heatpulse 2101 at Semicon West (Fig. 23). The 2101 was able to process 2" to 5" wafer diameters. The quartz chamber and reflector housing was basically the same as used in 210T. Lower serial numbers of 2101 monitor the wafer temperature with a removable "sensor" made of the same material that is to be annealed, placed on the wafer tray in close proximity of the actual wafer being processed (Fig. 24). A signal from K-type thermocouple mounted on the sensor. Although this relative temperature measurement works reasonably well at lower temperature, it can be completely misleading for processing at higher temperatures.

The later systems were retrofitted with pyrometer and have an ability to run HCl and

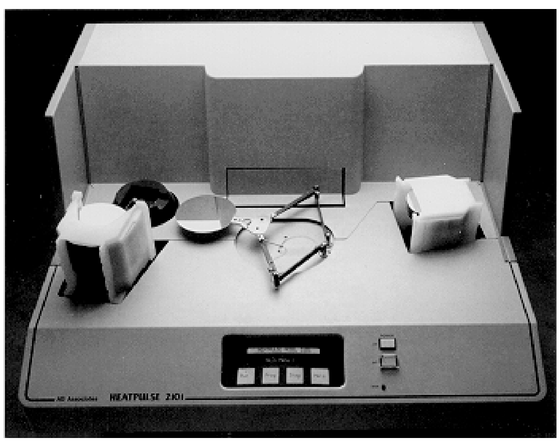


Fig. 23. AG Associates RTP system 2101 introduced in 1984.

ammonia. A later introduced system with the same capabilities, able to run 6" wafers was Heatpulse 2106.

The 2101 had numerous reliability problems and software crashed regularly. New program always need to be entered manually.

After disappointment with IA-200, Varian introduced and delivered in December 1985 a lamp based RTP system (the manual RTA-800 and the automated RTP-8000). Systems were well executed, however, by this time AG Associates had a commanding lead in market because they were addressing non-implant applications of RTP (silicide). Non-implant applications were not well matched with the implant business in Gloucester and the Varian RTP product line was killed around 1990.

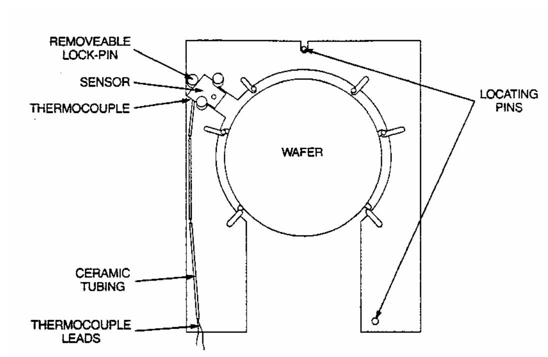


Fig. 24. AG 2101 wafer tray with installed TC for temperature monitoring.

In February 1984 Ronald E. Sheets of Tamarack Scientific Company in Anaheim, CA filed patent application " Apparatus for Heating Semiconductors Wafers in Order to Achieve Annealing, Silicide formation, Reflow of Glass Passivation Layers, etc." (U.S. Patent # 4,649,261). Approximately at the same time the company started marketing "Radiant Impulse Processor – Model 180" (Fig. 25). Model 180 was a fully automated cassette to cassette system with wafer temperature controlled by pyrometer and closed loop controller. System configuration of Model 180 is based on the idea of so called "Light Pipes" previously known in optical engineering. The basic principle is described in Sheets patent as

following: "radiation energy entering non-uniformly into entrance of integrating light pipes (i.e. cavity with highly reflective and non-diffusing surface) will be uniform by the time the radiation energy reaches the exit of the pipe (Fig. 26).

As for any new idea, at the time when "mind conditioning" by competitors was in progress Tamarac Scientific was not able to succeed.

They never built any other RTP system and returned to its original business – photolithographic exposure systems for printed circuit boards and laser photoablation systems.

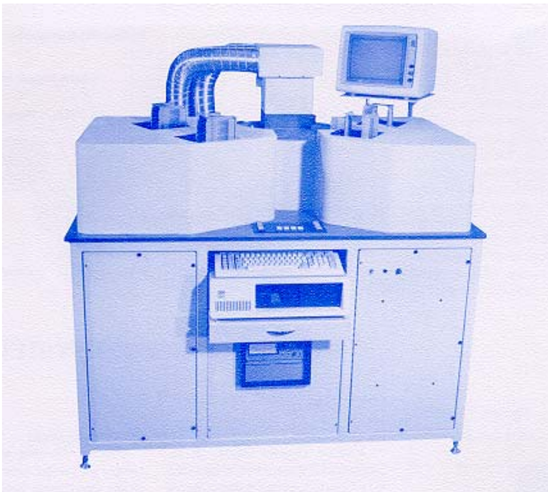


Fig. 25. TAMARACK RTP system Model 180

Probably nobody noticed that in 1985, in Munchen, former ASM employees G. Kaltenbrunner and P. Augustin with their wives put up their houses as collateral, borrowed money and formed AST Elektronik GmbH. In three years annual sales were about $ 4 million, mostly with diffusion systems and PECVD systems. During 1987, AST started an RTP project and in 1989 they had a system ready for sale. In a relatively short period of time, over 20 universities and research institutions together with Siemens, Philips and Telefunken bought AST RTP system SHS 100 (manual) or SHS 1000 (automated). In 1990, AST employed about 12 "heavy weight" engineers (H. Walk, T. Knarr, A. Tillmann, Z. Nenyei) and about 30 other personnel, RTP became the only products AST manufactured.

The "AST Photon Box" (Fig. 27) has unique features, such as double-OH-band quartz processing chamber, slip guard ring, gas distribution, and mainly unmatched software capabilities. AST management knew that they did not understand phenomena involved in RTP.

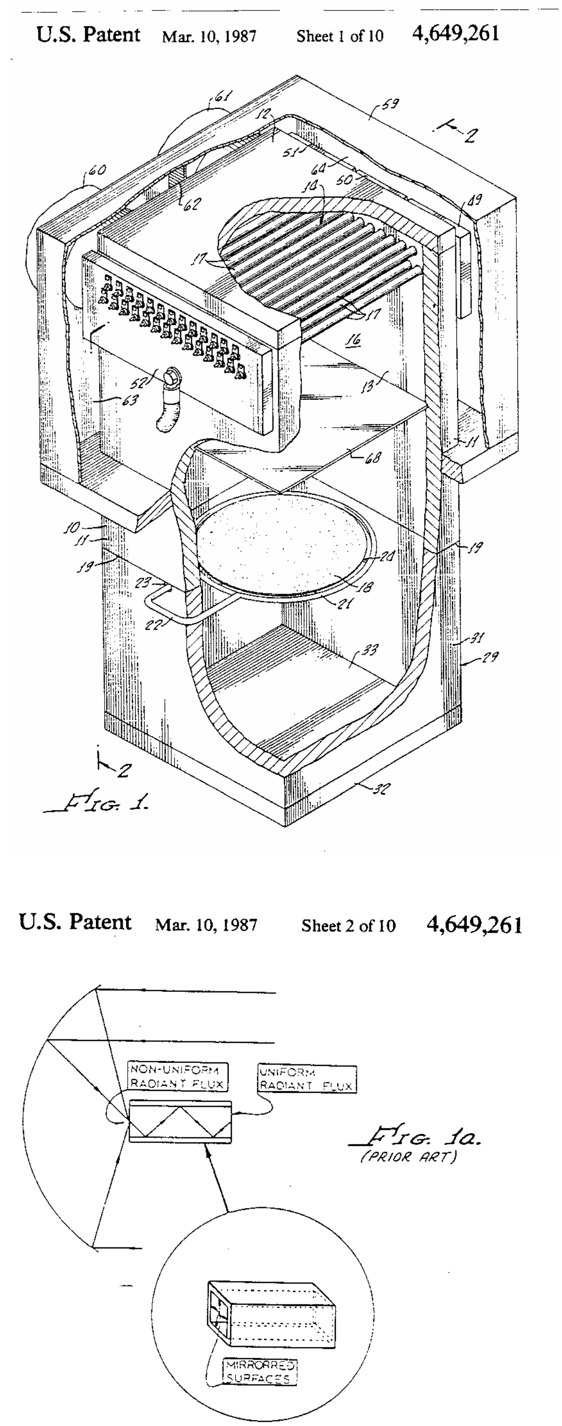


Fig. 26. TAMARACK patent describing the concept of "Light Pipes"

Instead, making them invisible, like some competitors, they decided to equip tools with complete data acquisition capabilities, measuring and recording almost all that can be measured. When the system was later upgraded with independent digital power lamp control, improving already very high reliability and up-time, the market dominance of AG Associates and Peak Systems started to erode.

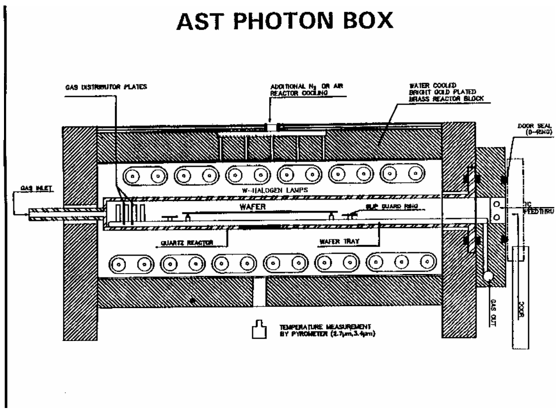


Fig. 27. AST Elektronik "Photon Box" introduced in 1988

In 1988 TI, sponsored by DARPA and by the Air Force launched a project "Manufacturing Science and Technology" (MMST) to develop manufacturing equipment with the objectives of reducing cost of manufacturing and cycle time. Program feasibility had been demonstrated on 0.35 µm logic CMOS process with a cycle time of 3 days.

The MMST equipment consisted of 19 single wafer processors designed by TI, plus 15 commercial single-wafer tools. The new RTP system with modular reflector chamber, showerhead, multi-zone illuminator shown in Fig. 28, multi-point temperature sensor, and multizone temperature controller was a unique concept in comparison with market dominating systems of AG Associates and Peak Systems.

The project resulted in numerous patent applications but in reality the project "diffused" only licensing technology to CVC Products in Rochester. CVC introduced "The Connexion" RTP module in 1995 without any major success.

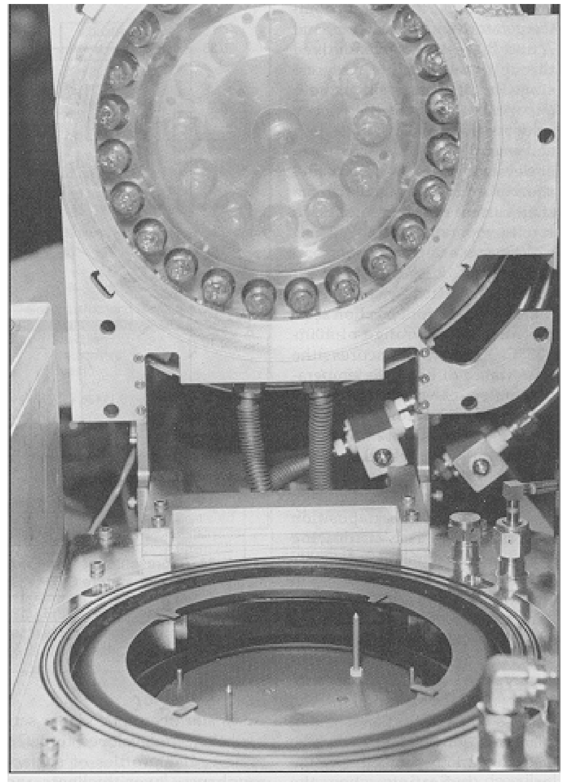


Fig. 28. Texas Instrument MMST RTP Module

EARLY MODELING WORK OF DIFFUSION DURING RTP

In 1983, R.B. Fair, J. J. Wortman, and J. Liu of MCNC North Carolina reported at the IEDM a detailed experimental study and simulation model of diffusion of ion implanted dopants in Si during RTA.

The unanswered question at that time was what mechanism controlled the diffusion of implanted dopants in Si during very short time anneals. Numerous unquantified models were put forth by workers around the world, but no one had tried to simulate the rapid transient effects that were observed experimentally.
Fair's group found that the diffusion transient was associated with the dissolution of implant damage in the Si. The simulation model included the calculation of diffusion during the rapid temperature ramp up and down, and overlaid on this calculation was the transient point-defect response associated with implant damage annealing. Since this early work was

performed a large number of publications have described damage-assisted diffusion.
From all proposed models it is not clear if damage-assisted diffusion is different in the case of electronic excited semiconductor. Very early study of annealing of semiconductors performed by Bell Labs [17] noted that annealing of Germanium depends strongly on the type of conduction, concentration of defects, and any additional illumination during annealing. At that time common belief was that charge exchange between lattice imperfection result in their higher mobility. Later Hayens [18], using spectroscopic data, showed that radiation produced by recombination of excess carriers is a function of photon energy of incident radiation. The key question clearly is: are migration properties of the excited system different from those of the fundamental one ? Very early experiments of Rapid Thermal Annealing of implanted layers with different heating rate indicate that there is an athermal component of annealing, depending on the wavelength of optical radiation and properties of implanted layers.
Diffusion under non-equilibrium conditions during RTA is still not well understood and no reasonable model is available.

TEMPERATURE MEASUREMENT

Laser annealing practitioners were not to much concern about sample annealing temperature. For both pulsed laser mode and CW mode there is no known method to measure sample surface temperature.
The measurement temperature in the first RTP system was mostly based on the optical pyrometer. Sato [19] characterized emissivity of ultra pure optically polished silicon as a function of temperature. Sato emissivity data were used to adjust the pyrometer. The problem is that the semiconductor substrate used in semiconductor manufacturing is not the ultra pure material described by Sato. In the majority of situations the wafer is covered on both sides by several thin layers of different materials and typically the edges of the front sides of product wafers are not doped, contrary to doped patterned region.
As soon as RTP systems with better data acquisition capabilities became available, it was clear that varying emissivity of wafer is the major problem with pyrometer temperature measurement. At Sematech RTP workshop in 1990, author presented data comparing power needed to maintain the steady temperature of two wafers with the same “Dt”: one annealed with slow, and second with fast heating rate (Fig. 29). Due to the changes in wafer emissivity the power at steady-state is different.

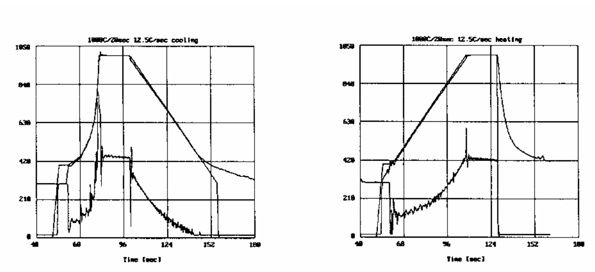


Fig. 29. Variation in steady-state power due to the changes in emissivity of two wafers annealed with different heating rate.

Only after the pioneering work of Chuck Schietinger, who experimentally proved that emissivity of the wafer is changing during processing (Fig. 30), RTP community acknowledge that conventional pyrometer will not work.
AST and AG introduced almost at the same time a “temporary solution”. The so called HotLiner and Hot Plate separate the wafer from the optical path of the pyrometer. Pyrometer senses the temperature of the body with constant emissivity. This solution is equivalent to reduction of lamp blackbody temperature, however, the fundamental problems remain unchanged.

Peak and especially AST developed a good pyrometer calibration practice based on TC measurement. However, because each product needed to be calibrated, process engineers never liked the cumbersome work with TC instrumented wafers.

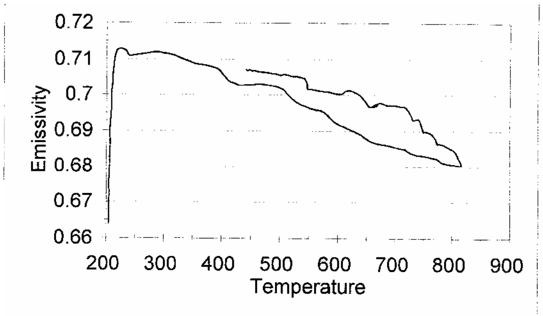


Fig. 30. Emissivity of un-pattern wafer during RTP processing [Schietinger 1995]

The thermocouple is still the most accurate device for measuring the temperature of the wafer during RTP processing but the measurement requires experience and is very costly. The thermocouple assembly and its attachment to the thin wafers are also sources of error and uncertainties. The poorly installed TC may easily result in errors bigger than 40 ^{o}C. V.A. Labunov in 1984 analyzed the measurement error for wafer instrumented with TC and for TC supporting wafer [20]. Results showed errors up to 40 and 70 ^{o}C for embedded and supporting TC, respectively.

Zsolt Nenyei described a story about acceptance of RTP tool at Rockwell: Rockwell insisted on TC measurements and asked for temperature uniformity less than 5 ^{o}C based on measurement of 17 TC across 8 " wafer. AST application engineers worked for a week to tune the power distribution to the lamps to achieve target. In addition they wasted about $ 20k in used monitor wafers. Two years later SensArray disclosed that the design of TC assemblies used on the Rockwell wafer, result in error as large as +/- 10 ^{o}C.

The measurement of wafer temperature was the top subject in mind conditioning of customers. With each newly introduced RTP tool there were also promises that "finally system with temperature measurement which works" arrived. AG introduced dual wavelength pyrometer, Peak System introduced temperature measurement based on the thermal expansion of the wafer, AST announced "Pin TC" temperature measurement, etc. Any of these "breakthroughs" did not work and the temperature measurement became the main obstacles in acceptance of RTP systems by industry.

Although, as mentioned earlier, there may be some athermal component of annealing present, most annealing properties are determined by temperature. There is one important consequence of the irreproducible and inaccurate temperature measurement: most of the work and experiments describing diffusion behavior of semiconductors is accompanied by uncertainty of the temperature of the sample. Frequently, the hypothesis about the atypical diffusion in RTP systems is just a consequence of unknown or incorrectly determined processing temperature.

APPLIED MATERIALS

In 1986 applied Materials started the program "Mainframes and Process Integration". The goal of the project was to develop a multi-chamber processing platform for sequential or integrated processing of individual steps under single vacuum. It was expected that this type of processing will reduce process time, improve micro contamination control, and enable processing that could not be performed in non-integrated environment.

The project resulted in a platform called the Precision 5000 and was introduced to the market in 1987. The system was originally developed around CVD and dry etch chambers (Fig. 32). The platform became a success and created a breakthrough in process technology and system architecture. At that time, this was an extraordinary system and was Applied Material's first step to future single wafer, multi-chamber architecture with a highly

Precision 5000 has become the archetype for the "cluster tool" concept, which envisioned integrated processing with "mix-and-match" process chambers.

Within the next five years, Applied installed over 1000 Precision 5000 system worldwide.

The improved system resulted in what is today known as the Endura and Centura platforms.

In 1989 Applied Materials invested 10% into privately held Peak Systems and both companies agree to develop RTP modules that could be mounted on the Precision 5000.

Former employee of AG Associates, Jaim Nulman, has became Applied Materials

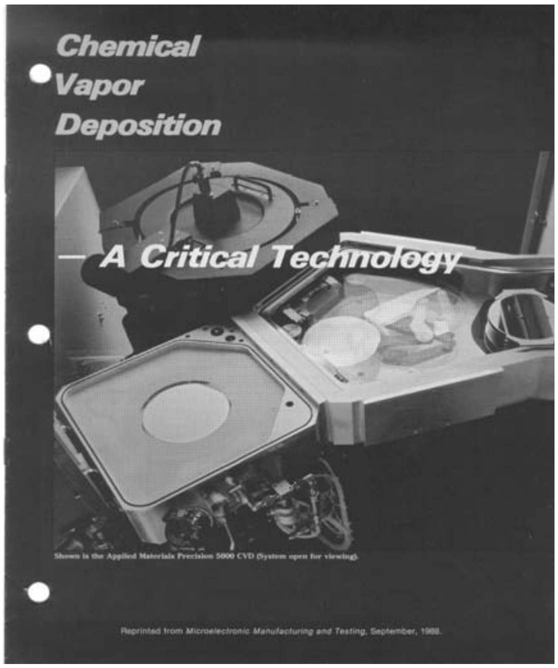


Fig. 32. Applied platform Precision 5000

manager running the Peak-Applied joint program.

From day one the program was not running well. Applied blamed Peak for late delivery, and performance not meeting the specification. After a while, the Peak module mysteriously exploded in the Applied lab and Applied and Peak Systems relationship ended up in court (Fig. 33) . The suit started a series of Applied Materials legal litigation with ASM, AG and AST.

In the mid 80's, a group of Prof. Jim Gibbons Ph.D. students (Chris Gronet, Judy Hoyt, Jim Sturm, Cliff King) at Stanford worked on several projects known as "Limited Reaction Processing" – RTA based epitaxy and heteroepitaxy, polysilicon epitaxial alignment, etc. They were using relatively simple home built RTP system with linear lamps.

In 1988, Prof. J. Gibbons and Chris Gronet incorporated G-Squared Semiconductor Corporation, with the goal to manufacture the RTP equipment based on the idea of light pipes conceived by Chris and Dr. Gibbons. The business started with a close relationship to TI. G-Squared delivered six RTP "heaters" for TI's single wafer equipment development and initiated a relationship with HP. In January 1990 Gronet and Gibbons filed a patent

12/17/90

Peak Sues Applied Materials

FREMONT, Calif. — Peak Systems Inc. last week filed a suit against Applied Materials charging the firm with fraudulently appropriating trade secrets related to a rapid thermal processing technology during a joint development program between the companies.

The suit claims that Applied covertly developed a competitive RTP process chamber for its Precision 5000 line during the program.

Peak's complaint alleges Applied's behavior "was part of a long-established pattern of anti-competitive conduct," noting Applied "has previously entered into other joint enterprise or development agreements with potential competitors without intending to perform the agreement, but for the true purpose of gaining access to its competitors' valuable, confidential and proprietary information.

"In each case, AMAT (Applied) interfered with the performance of the agreement, thereby assuring the failure of the joint enterprise or development effort. Thereafter, AMAT developed a competitive, substitute product

See APPLIED, Page 4

Applied Materials Hit With Peak Secrets Suit

Continued From Page 1

wrongfully using the trade secrets and confidential proprietary information acquired through the joint enterprise or development effort to its own benefit."

Applied and Peak began to collaborate more than a year ago. Besides the joint project, which called for the development of an RTP module that could be mounted on the Precision 5000, Applied agreed to make an equity investment in Peak, paying for a 10 percent stake in the privately held firm (EN, Sept. 18, 1989).

The suit filed in Santa Clara County Superior Court charges Applied with fraud and deceit, negligent misrepresentation, misappropriation of trade secrets, unfair competition, unjust enrichment and trade libel, among other allegations. Applied's legal counsel declined to comment last week.

The 22-page complaint blames the Peak-Applied project director, Jaim Nulman, for many of the problems Peak alleges. According to the suit, Dr. Nulman, an ex-employee of Peak's principal competitor, AG Associates Inc., was given specific instructions by Applied management to delay Peak's efforts to integrate its module on to the Precision 5000. The suit also asserts Dr. Nulman heads up a secret RTP project at Applied to build a module to replace Peak's on the 5000.

"AMAT worked on its secret project to develop a replacement RTP module while having access to Peak's confidential and proprietary trade secrets and while encouraging Peak to continue to make full disclosure of its trade secrets in pursuit of the joint enterprise... Jaim Nulman, the AMAT employee in charge of the Peak-AMAT joint enterprise, was simultaneously the AMAT employee in charge of AMAT's secret project to develop a replacement RTP module," the complaint says.

Peak president and chief executive Timothy Stultz last week said the joint development agreement prevented Peak from working with any other equipment firms to integrate its RTP module on to their platforms. Dr. Stultz said his company is convinced that Applied, which has allegedly not allowed Peak to participate in any joint sales activities, is actually selling its own RTP module as an alternative to the Peak system.

"They assured us it was simply a contingency plan, but they were marketing their alternative to mutual customers," Dr. Stultz said. "We were never allowed to co-market with them. We were only going to work with Applied and we turned down the opportunity to work with other systems integrators. Clearly, this was damaging to us in the marketplace."

The incidents which led to the breakup included the explosion of a process chamber, according to the Peak suit.

"In June 1990, the RTP 5000 module exploded while in the possession and under the control of AMAT," claims the suit. "Peak is informed and believes... that AMAT employees through negligence or deliberately caused the explosion. After Peak repaired the module, AMAT failed and refused to run a series of controlled experiments to determine the cause of the explosion to avoid any recurrence."

Dr. Stultz said his firm is asking for damages, the termination of the partnership between the two firms and a court order preventing Applied from using Peak technology in any of its product offerings. He also indicated the Peak will begin searching for other integrator companies to work with to find another market entry for its module.

— ERIC WINKLER

Fig. 33. The beginning of "New Legal RTP Era".

application, "Heating apparatus for semiconductors wafers and substrates", which later became U.S. Patent # 5.155,336 (Fig. 34).

With about 10 employees, they were ready to prototype a honeycomb reflector module, based

High Temperature Engineering concept generated a lot of interest. Arnon Gat of AG wanted, at the time when AG was blooming, to buy the license. The deal did not go through, and struggling HTE was later acquired by Eaton.

Obviously, some form of concept introduced by Lee, which is today called small batch furnace, or fast ramp of furnace, may be a reasonable alternative to lamps based RTP systems.

Fig. 36. THE Corporation RTP system Reliance

NOT FINISHED PROJECTS

One of the main problems of RTP, is a lack of understanding of physical processes that occur in a semiconductor under intense optical radiation. Additional difficulties arise from poor understanding of heat transfer in semitransparent material, such as semiconductor substrate covered with single or multiple thin film layers of different materials. Since the beginning RTP vendors pay only very scattered attention to this aspect. Some of the start up companies introduced good new ideas. Process Product Corporation, for example, designed and delivered to GTE, a small batch RTP tool shown in Fig. 38. A good idea accompanied by problems of new and small company, died very quickly. Process Product technology was sold to CVC in Rochester and was never introduced again.

Fig. 38. Small batch RTP tool designed by Process Product Corporation.

Very likely the most promising RTP prototype was designed by Matrix at the beginning of 90's.

The tool was designed around a temperature measurement concept developed by Kiefer Elliot. The pyrometric temperature system (called TEASYS) measures continuously wafer emissivity and compensates for lamp light interference and chamber reflectivity effects. The Light Pipe reflector (Fig. 39) was based on best accumulated knowledge at that time. After first promising runs, Fred Wong, who moved to the top of Matrix and who previously founded Rapro, knowing how risky is to be in RTP business, stopped project.

There are several new technologies related to the RTP which are not yet explored. One of them is annealing during the implantation. In 1988 Y. Erokhin group reported [18] significant changes in properties of implanted layer exposed to optical radiation with energy above the energy gap during implantation.

Prof. H. Ryssel of Frauenhofer Institute in Erlangen designed RTP chamber on Varian 350D implanter (Fig. 40).

Fig. 39. The Matrix System 10 RTP system

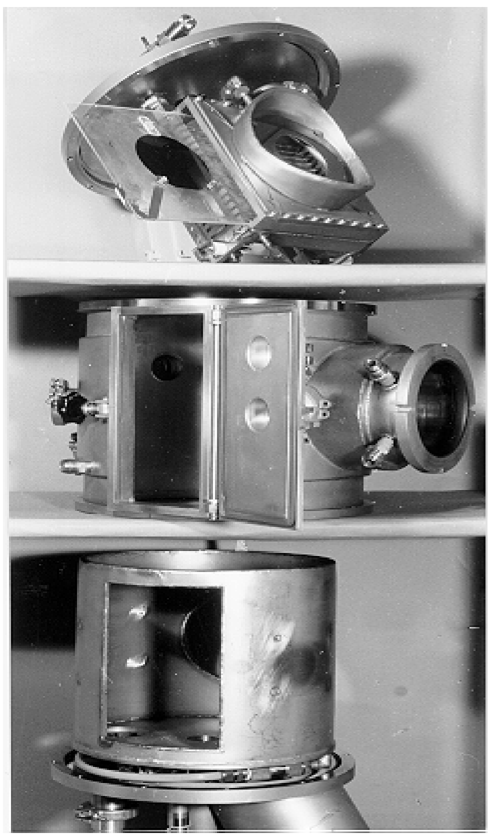


Fig. 40. RTP chamber retrofitted into Varian 350D implanter [Ryssel 1991]

The RTP chamber used 15 lamps with a total power 15 kW. The maximum wafer temperature was 1100 ^oC with a heating rate of 100 ^oC/sec.

The apparent diffusion coefficient has a maximum at 800 ^oC and it is several orders higher than the intrinsic diffusion coefficient. It has been found that diffusion coefficient is proportional to the square root of the dose rate. Obviously, such processes may offer new applications for RTP such as ion beam mixing or ion synthesis of SOI layers.

VORTEK Industries has struggled for years to launch RTP equipment. The VORTEK lamp is considered by many as the most suitable source of the radiation for annealing of Si implanted layers. The VORTEK's main problem is that today the semiconductor industry does not want participate in co-development of manufacturing tools.

Sematech, and SRC did not contribute to development of RTP technology in a measurable way. In reality, politics in early years of Sematech delayed Applied Materials projects for malicious reasons such as, for example, MESC compatibility.

Several universities (Stanford, NCSU, UT) demonstrated good ideas, however these organizations mostly only launched ambitious (and frequently not realistic) projects and ended with no funds.

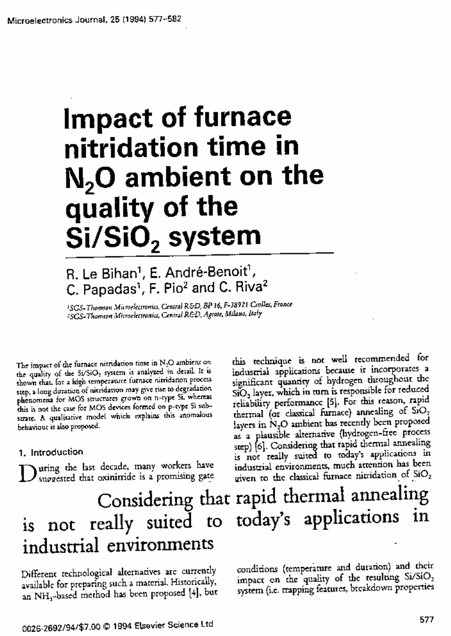
CONCLUSION

Motto:

"Cynicism often comes with experience"

It is interesting to see with distance the approach of the scientific community working on laser annealing and the approach of the engineering community working on RTP. The scientists analyzed laser energy deposition to the semiconductors from the first principle and they developed a very reasonable level of understanding of involved physical phenomena. To the contrary, the RTP engineering community frequently ignored experimental evidence and physics, and with the help of "mind conditioning" they were able to sell "rubber banded" systems.

Gradually several people from the RTP community made a fortune. There is no one who made money on laser annealing. While the laser annealing is not considered in any roadmap as a manufacturing technology, RTP market grew significantly.



Microelectronics Journal, 25 (1994) 577–582

Impact of furnace nitridation time in N_2O ambient on the quality of the Si/SiO_2 system

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The impact of the furnace nitridation time in N_2O ambient on the quality of the Si/SiO_2 system is analyzed in detail. It is shown that, for a high temperature furnace nitridation process step, a long duration of nitridation may give rise to degradation phenomena for MOS structures grown on n-type Si, whereas this is not the case for MOS devices formed on p-type Si substrate. A qualitative model which explains this anomalous behaviour is also proposed.

1. Introduction

During the last decade, many workers have suggested that oxinitride is a promising gate

Considering that rapid thermal annealing is not really suited to today's applications in industrial environments

Different technological alternatives are currently available for preparing such a material. Historically, an NH_3-based method has been proposed [4], but this technique is not well recommended for industrial applications because it incorporates a significant quantity of hydrogen throughout the SiO_2 layer, which in turn is responsible for reduced reliability performance [5]. For this reason, rapid thermal (or classical furnace) annealing of SiO_2 layers in N_2O ambient has recently been proposed as a plausible alternative (hydrogen-free process step) [6]. Considering that rapid thermal annealing is not really suited to today's applications in industrial environments, much attention has been given to the classical furnace nitridation of SiO_2 conditions (temperature and duration) and their impact on the quality of the resulting Si/SiO_2 system (i.e. trapping features, breakdown properties

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Fig. 41a. Comments Regarding RTP performance published in 1994.

The concept of RTP has a several advantages such as higher level of activation of implanted layers, the capability to create sharp interface in layered structures and the capability to enable a new processing technique which needs precisely controlled and quickly changed reactive ambient. The major effort of RTP needs to be based on these features, including the concept of clustering which can change the manufacturing dramatically.

Due to the lack of systematic work the current generation of RTP tools deviate from the original concept of RTP processing due to the problem with temperature measurement. The RTP equipment available at market now reduced the radiation source blackbody temperature, and is converging to the "single wafer furnace" mode. AST and AG introduced HotLiner and Hot Plate, Applied is recommending to maintain the lamps at the idle during the wafer transport. Despite the fact that many problem remains, the RTP gained acceptance by many.

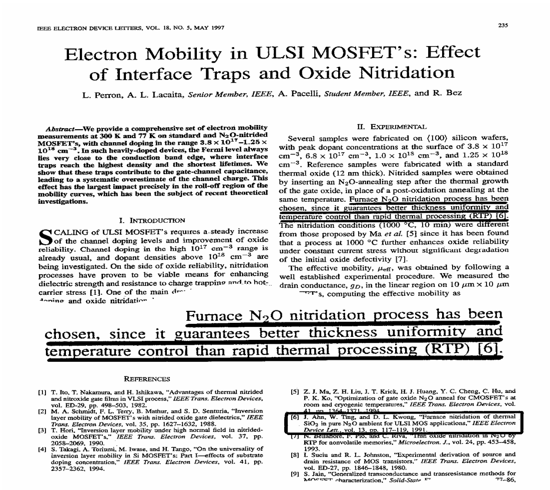
Today, no one is questioning the fact that RTP equipment may enable a viable technology, which may result in a new method of thermal processing even if there are still warnings from the users not recognizing RTP as a manufacturing process (see for example Fig. 41a and 41b).

The semiconductor manufacturing trend is heading towards single wafer processing due to the advantage in shorter cycle time. Back end of processing is already based on single wafer tools processing. However, single wafer tools have no capability to monitor processing conditions. In-situ diagnostic capabilities are very important, if processing uses an elevated temperature and is as complex as RTP. Repeatability of the processing will be obviously a major challenge for future RTP technology.

An interesting point is also that RTP is one of few equipment technologies which has not succeeded in Japan and no Japanese company at any time in any way penetrated the market. There were marketing attempts by Kokusai in early 80's (Fig. 42), and later by DNS, they all failed.

In the past, physicist used fundamentals to understand fully and thoroughly the technology, then handed it off to engineers. However, academic - like research has decreased significantly during last decade. Small companies may traditionally fill the gap between research laboratories and big corporations. The key role of small companies is to develop risky projects and survive long enough to develop an innovative technologies. Low risk, high gain projects are best, of course. In real life, there is no such thing as a free lunch, and developing new technologies often requires levels of risk that industry giants find unacceptable.

The RTP industry after years of chaotic development ended at the point where only Applied Materials and STEAG RTP offer RTP tools for high volume manufacturing, with no small company in business,



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Electron Mobility in ULSI MOSFET's: Effect of Interface Traps and Oxide Nitridation

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***Abstract*—We provide a comprehensive set of electron mobility measurements at 300 K and 77 K on standard and N_2O-nitrided MOSFET's, with channel doping in the range 3.8×10^{17}–1.25×10^{18} cm^{-3}. In such heavily-doped devices, the Fermi level always lies very close to the conduction band edge, where interface traps reach the highest density and the shortest lifetimes. We show that these traps contribute to the gate-channel capacitance, leading to a systematic overestimate of the channel charge. This effect has the largest impact precisely in the roll-off region of the mobility curves, which has been the subject of recent theoretical investigations.**

I. INTRODUCTION

SCALING of ULSI MOSFET's requires a steady increase of the channel doping levels and improvement of oxide reliability. Channel doping in the high 10^{17} cm^{-3} range is already usual, and dopant densities above 10^{18} cm^{-3} are being investigated. On the side of oxide reliability, nitridation processes have proven to be viable means for enhancing dielectric strength and resistance to charge trapping and to hot-carrier stress [1]. One of the main dr... doping and oxide nitridation ...

II. EXPERIMENTAL

Several samples were fabricated on ⟨100⟩ silicon wafers, with peak dopant concentrations at the surface of 3.8×10^{17} cm^{-3}, 6.8×10^{17} cm^{-3}, 1.0×10^{18} cm^{-3}, and 1.25×10^{18} cm^{-3}. Reference samples were fabricated with a standard thermal oxide (12 nm thick). Nitrided samples were obtained by inserting an N_2O-annealing step after the thermal growth of the gate oxide, in place of a post-oxidation annealing at the same temperature. Furnace N_2O nitridation process has been chosen, since it guarantees better thickness uniformity and temperature control than rapid thermal processing (RTP) [6]. The nitridation conditions (1000 °C, 10 min) were different from those proposed by Ma *et al.* [5] since it has been found that a process at 1000 °C further enhances oxide reliability under constant current stress without significant degradation of the initial oxide defectivity [7].

The effective mobility, μ_{eff}, was obtained by following a well established experimental procedure. We measured the drain conductance, g_D, in the linear region on 10 $\mu m \times 10$ μm ...T's, computing the effective mobility as

Furnace N_2O nitridation process has been chosen, since it guarantees better thickness uniformity and temperature control than rapid thermal processing (RTP) [6].

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Fig. 41b. Comments Regarding RTP performance published in 1997.

In an idealistic world, users may decide between: small batch furnace, single wafer furnace or lamp based RTP, whichever performs better. However, because to globalize economy with one or two vendors of semiconductor equipment, we may not see once again the best technical solution, but only the solution which will be marketed.

At the 1st RTP Conference in 1993 I quoted from the letter I received from Prof. David DeWitt who characterized status quo at that time: *"my prediction is that three years from now your industry will still be seeking to understand in what manner the optical properties-especially emission and transparency problems-of films influence radiometric method of determining temperatures. The recent events provided further evidence that scant attention is being made to new technologies created by exploring new science. Evidence suggests an empirical approach that somehow works is preferred to developing understanding of phenomena"*.

Obviously the same is still true today.

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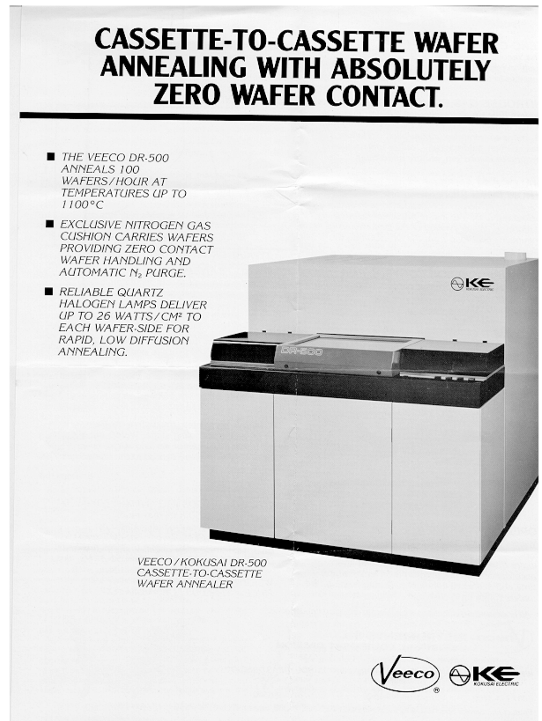

Fig. 42. Kokusai RTP system unsuccessfully marketed in U.S in early 80's.

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