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Design and development of the laboratory scale rapid thermal processing (RTP) system

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Abstract

A key requirement in achieving successful submicron fabrication processes is the control of the thermal budget. This has created a considerable interest in transient methods of thermal processing, which minimize the negative influence of high-temperature processes on semiconductor crystals. In brief, transient heating derived from rapid thermal processing can promise a lot of advantages. The emergence of this important processing technique has led to a rapid growth of research activities in this area involving all types of processes. The objective of this research is to design and develop a laboratory scale furnace system. Experiments conducted through deposition and doping processes on silicon wafers using the constructed system have revealed the superiority and advantages of the system over the conventional ones, in particular, the shorter time scales (measured in seconds), the reasonably low temperatures and the sheet sensitivities produced. This type of system would open a vast scope of research at the laboratories without the huge investment on the commercial rapid thermal system.

Key word: Design, rapid thermal processing (RTP), control, development, integrated circuit (IC).

INTRODUCTION

The current trend of miniaturization of integrated circuit (IC) elements in the development of microelectronics demands for successful fabrication processes of submicron structures. One of the most effective methods of controlling phase-structure, properties, and electro physical parameters of materials and ICs is the thermal processing. Conventionally, this process takes a longer duration, ranging from tens of minutes to several hours. However, with rapid thermal processing, shorter time scales, normally in seconds can be achieved.

This transient heating offers a number of advantages including the opportunity to modify material properties of the semiconductor in the solid phase combined with minimal negative effects at high temperature. Negative effects include diffusion redistribution of dopants, generation of defects and carrier traps in the oxide and at the semiconductor-oxide interface. Over the past 15 years, there has been a rapid growth of research activity for all types of processes, ranging from annealing of ion implant damage (Correra, 1980), dopant diffusion (Davies, 1986), gettering (Sparks, 1986), oxidation (D’Heurle, 1986), nitridation, and chemical vapour deposition of a range of materials (Hsieh, 1991).

Traditionally, rapid thermal processing (RTP) is used for defect annealing, recrystallization, and activation of doped implanted layers. The study here focuses on RTP operating in the heat balance regime with incoherent light and short heating times (Sedgwick, 1983). Thermal processing regime of heat balance occurs when the pulse duration is long enough to have uniform temperature distribution in the wafer. Using halogen lamp as the radiation source, this type of thermal processing regime can be produced and has been widely applied because of its simple technical implementation. The reduced temperature gradient of this rapid process can cause a reduction in the elastic stresses and consequent defect generation in the wafers.

Solid-state processes initiated in semiconductors by RTP are mainly of thermal origin and hence there are many similarities with conventional furnace annealing. However, the much shorter processing times, rapid heating and cooling are the main distinct features. The non-equilibrium fast transient processes occurring can introduce structural changes during the initial moment of the thermal processing (Borenstein, 1986; Adekoya, 1987).

METHODOLOGY

Experimental details

The constructed RTP system is divided into several main parts, namely the heating source, reaction furnace, lamp holder, and reflector and temperature control system. Halogen tungsten lamp is chosen because the incoherent radiation produced, it can provide a uniform temperature profile to the wafer (Borinsenko, 1984). Here, 12 lamps of 1000 W were used as the heating source. They emit 55% of the radiation produced in the wavelength range of 0.4 to 4.0 mm.

Quartz tube was used as a reaction furnace because of its capability in withstanding high temperatures, between 1700 to1800°C and resistant to thermal shock and also 80% reflectivity in the wavelength range of 0.27 to 2.0 µm. The lamp holder consists of two pieces of circular plate of diameter 21.5 cm, it has a hole at the centre to house the quartz tube of diameter 8.4 cm. Halogen tungsten lamps will be connected to the sockets attached to the circular plate. Both plates were connected with each other with a stainless steel rod. A stainless steel cylinder of 21.5 cm diameter and 3 mm thick was used as the reflector. The outermost layer of the system is the concrete cylinder of thickness 2.0 cm, which acts as the insulator. The lamps are controlled by the automated system control, solid-state relay and thermocouple.

Here, a comparative study was made between conventional and rapid thermal processing for doping process. Rapid thermal processing would use the constructed system shown in Figure 1, while the conventional processing required a conventional furnace. In the conventional system, the copper tube coils surrounding the quartz reaction tube act as the heating source. The temperature is maintained by the control power provided by a copper tube coil.

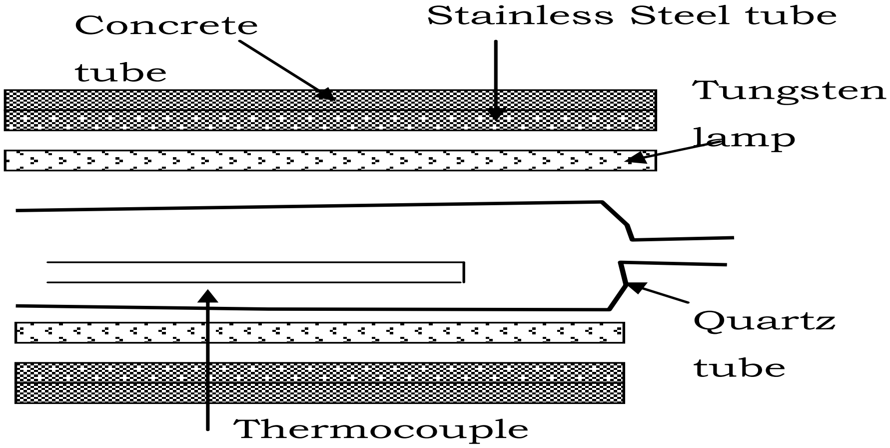

Figure 1. Configuration of RTP system.

Heat transfer in RTP systems involves the radiation mechanism between the tungsten filament and substrate where the latter has a much lower temperature. In this way, the sample will be heated directly through radiation causing the temperature of the wafer to rise up rapidly. Unlike RTP, the heat transfer mechanism in the conventional furnace involves transferring of heat from copper coil to the mullite tube which acts as a heat reservoir to heat the sample. This method takes a longer time to reach a high temperature.

Difference between the conventional and RTP furnace does not limit the rate of heating and cooling only, but also the mechanism involved in the thermal reaction. With a conventional system, the radiation source emit infrared and long wavelength radiation spectrum whereas RTP system ranges from short infrared wavelength to ultraviolet wavelength.

A thin film of spin-on diffusion source was deposited onto clean silicon wafer (p-type with orientation 11) using spinning technique. Spin-on dopant source of phosphorus with a concentration of 2 × 10^{21} cm^{-3} was used. Heat treatment processes involved are the pre-deposition and drive-in. The temperature for these diffusion processes is the same, at 800 to 900°C. But the processing times vary from 30 to 240 s for pre-deposition of conventional processing. In the drive in process, the processing time for RTP is 15 to 90 s whilst the conventional techniques require 10 to 40 min.

Wafer that had been deposited with dopant will be subjected to the pre-deposition process. The purpose of this heat treatment is to inject dopant atoms into the surface of the wafer. This will be followed by drive in process, intended to distribute dopant atoms into the wafer. Sheet receptivity can be measured by using the four-point-probe unit.

RESULTS AND DISCUSSION

Phosphorus from the traditional group-V dopants, is the fastest diffuser in silicon. This property determines the unique behaviour during RTP. Figure 2 shows the sheet receptivity (R_s) of phosphorus-doped silicon after a certain period of heating using incoherent light rapid thermal processing and conventional furnace at 850 and 900°C. It can be observed that R_s obtained in rapid thermal processing of range 40 to 60 Ω/sq. requires only between 20 to 90 s whereas in the conventional processing, R_s of 100 to 150 Ω/sq. needs about 10 to 40 min.

With slightly higher temperature of 900°C, R_s of 43.5 Ω/sq. can be obtained in 15 s for RTP as compared to the conventional method where 30 min would be required to achieve R_s of 46.1 Ω/sq. for both processing temperatures, lower values of R_s can be observed with RTP compared to the conventional processing. This implies that the diffusion enhancement of phosphorus in silicon can be achieved in a very much-reduced processing time, within seconds. Figure 3 displays sheet receptivity induced by RTP and conventional technique for phosphorus doping concentration of 2×10^{21} atoms/cm^3 at different processing temperatures. Sheet receptivity of RTP was found to be within the values reported by Nielsen (1983) who used different doping.

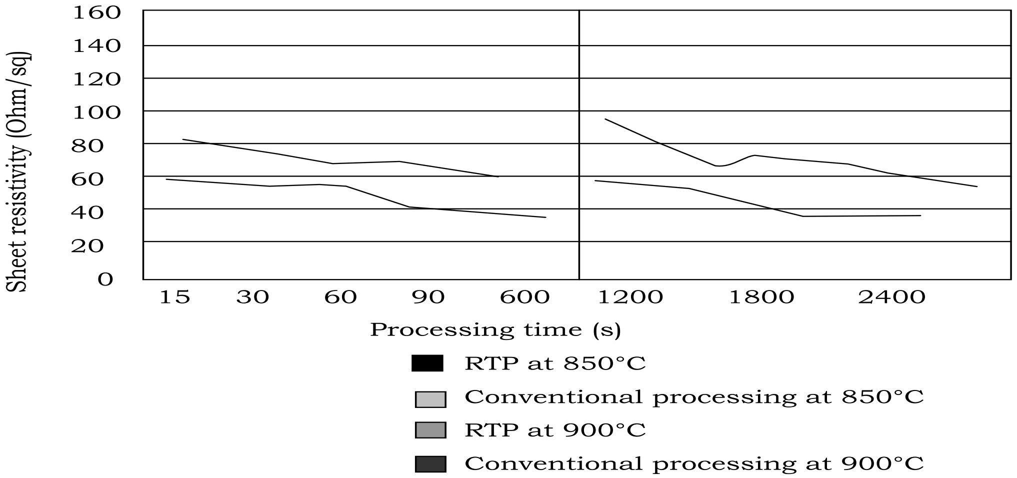

Figure 2. Sheet resistivity of phosphorus-implanted silicon layers as a function of processing time for RTP and conventional processing at 850 and 900°C

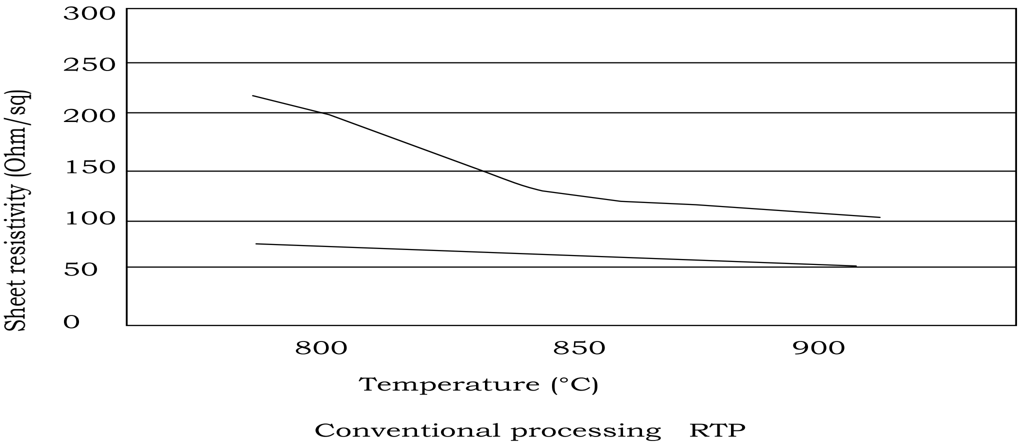

Figure 3. Sheet resistivity of phosphorus-doped silicon after RTP and conventional processing at different temperatures.

Higher values of the conventionally induced sheet resistivity were recorded here. In conventional processing, significant decrease of sheet resistivity from 800 to 900°C could be observed. This is believed to be associated with phosphorus depth redistribution. However, similar to Nielsen's observation, there is no obvious redistribution in the doped layer of RTP at impurity concentration of 2×10^{21} atoms/cm^3. On the other hand, enhanced phosphorus redistribution can be observed with doping concentration that is greater than 1×10^{16} atoms/cm^3. It was concluded that the observed differences could not be attributed to different concentration point defects, which are released during thermal processing. It seems that the occurrence of enhanced diffusion at concentrations beyond a certain critical value correlates with the steady-state phosphorus solubility in silicon. This leads to a suggestion that the cause of diffusion is created by dissociation of supersaturated phosphorus solution.

CONCLUSION

Clearly, the lower values of RTP induced Rs implies the enhanced diffusion of phosphorus taking place in the layer that is already recrystallized with the participation of mostly interstitial non-equilibrium point defects generated during RTP. Rapid heating of phosphorus-doped silicon crystals for time within seconds at a temperature of 900°C results in an enhanced diffusion of the impurity without any noticeable redistribution.

Results obtained from the experiment using the constructed RTP system have shown that this technique is capable of reducing thermal budget of fabrication processes by drastically reducing the processing time. Here, a comparative study on RTP and conventional processing has revealed the advantage of rapid processing as a result of the distinct features based on the non-equilibrium conditions created in RTP. Thus, by constructing the laboratory scale RTP system, many more distinct features produced by this much shorter processing times, rapid heating and cooling technique can be explored and investigated without huge investments in the commercial RTP system.

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