Thin, highly doped layers of epitaxial silicon deposited by limited reaction processing

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(Received 2 December 1985; accepted for publication 14 February 1986)

Limited reaction processing was used to deposit ultrathin, highly doped layers of epitaxial silicon. Multilayer structures consisting of alternating undoped and heavily boron-doped regions were fabricated *in situ*. The interlayer doping profiles of these structures, as determined by secondary ion mass spectroscopy, are abrupt. Van der Pauw measurements indicate that the electrical characteristics of the p^+ epitaxial films are comparable to bulk material.

The control of doping levels and depth profiles in semiconductors is critical for device fabrication. Currently, diffusion and ion implantation are two commonly used methods for introducing dopants into semiconductors. Very large scale integration (VLSI) devices, however, will require abrupt doping transitions and ultrathin, highly doped layers which may be beyond the capabilities of these techniques. Ultimately, a technology with the interface control of molecular beam epitaxy (MBE) and the doping range of chemical vapor deposition (CVD) will be needed.

In an earlier letter,[1] we introduced a technique called limited reaction processing (LRP) which has potential for both of these capabilities. LRP can be used to fabricate thin layers of semiconductors and insulators by precise control of thermally driven surface reactions. Radiant heat is used to produce large, yet rapid changes in the temperature of a semiconductor substrate. The substrate temperature, rather than the flux of a reactive gas, is used as a "switch" to turn a CVD reaction on and off. The substrate is hot only while a deposition or surface reaction is occurring, not during purging, gas flow stabilization, and other process modes. Thus, inherently, the thermal exposure of the substrate is minimized, reducing the broadening of interfaces by diffusion and intermixing. The advantages of a high-temperature process, such as good material quality and high dopant activation, can be realized while maintaining interface control. Moreover, by changing the ambient gases between high-temperature cycles, multiple thin layers of different composition can be grown sequentially without removing the substrate from the processing chamber. The LRP system and its application to the deposition of single layers of undoped epitaxial silicon have been described previously.[1] In this letter we demonstrate the ability of LRP to fabricate single crystal silicon structures consisting of ultrathin, highly doped regions with precise thickness control and abrupt doping profiles.

Heavily doped (100) and (111) 2-in.-diam silicon wafers were used as substrates for multilayer structures. For electrical characterization, p^+ layers were deposited on n-type (100) wafers with a resistivity of 3–10 Ω cm.

To calibrate the wafer temperature for a given lamp power versus time program and sample ambient, a W/26% Re vs W/5% Re thermocouple was electron beam welded to the center of a test wafer. Epitaxial depositions were then carried out on wafers without thermocouples. The radiant source consists of two banks of six tungsten lamps which are controlled by a microprocessor. These lamps can heat a wafer from 25 to 1200 °C in less than 3 s.

Multilayer structures consisting of alternating undoped and p^+ regions were fabricated to study layer thickness control and the abruptness of doping profiles. Samples were chemically cleaned and loaded into the LRP chamber. Multiple layers were then deposited sequentially *in situ* by changing the gas composition between high-temperature cycles. A typical processing procedure is shown below. *Note that the temperature transients for heating and cooling the wafer are on the order of three seconds, and that the wafer is cooled after*

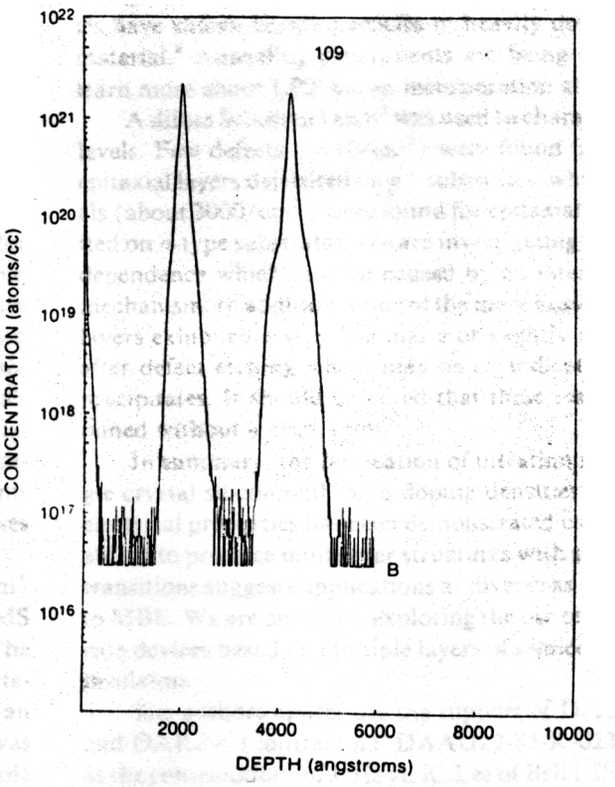

FIG. 1. SIMS profile of multilayer sample LRP 109. The incident beam was oxygen at 10 kV with a substrate bias of − 5 kV (Charles Evans and Associates). The first p^+ pulse deposited shows a slight amount of diffusion caused by the thermal cycles of subsequent layers.

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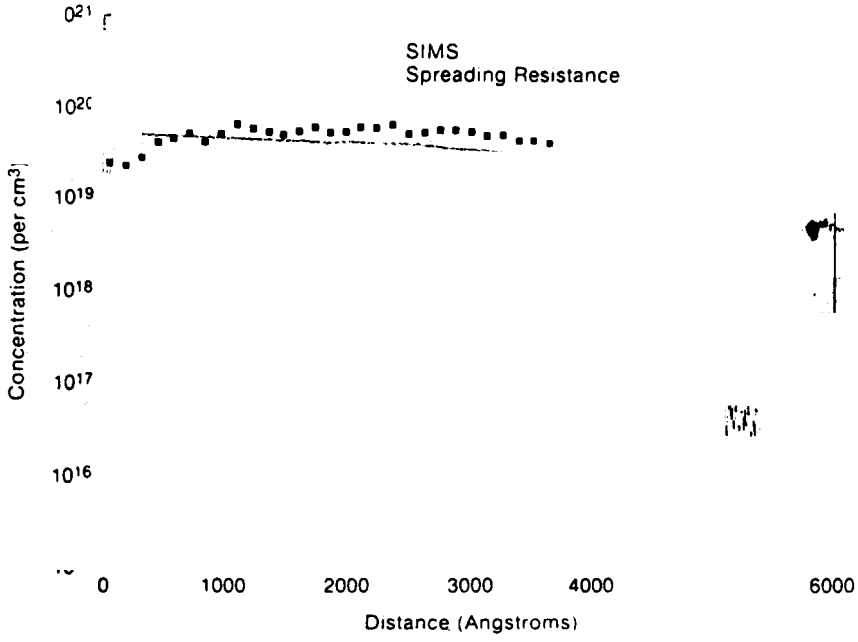

FIG. 2. Comparison of the SIMS (Charles Evans and Associates) and spreading resistance (Solecon Labs) profiles for sample LRP 82. The SIMS data are accurate only to about a factor of 2, so the level of boron activation depicted here is approximate.

each temperature cycle so that it is hot only for the time specified for each processing step.

(1) H_2 purge.

(2) H_2 bake at 1150 °C for 60 s at 500 Torr, 3 lpm.

(3) Cool, decrease pressure to 4.2 Torr, introduce SiH_4, let gas flow stabilize.

(4) Epitaxial deposition of undoped silicon in the range of 850–950 °C for 60 s.

(5) Cool, change H_2 to 5.2 ppm B_2H_6 in H_2, let gas flow stabilize.

(6) Epitaxial deposition of p^+ silicon in the range of 850–950 °C for 5–10 s.

(7) Repeat steps (3)–(7) for multiple p^+ "pulse" regions. Dichlorosilane was also used as a silicon source gas with similar results.

A typical secondary ion mass spectroscopy (SIMS) profile of a sample with two p^+ regions is shown in Fig. 1. p^+ pulses with a full width at half-maximum value of 10 nm can be reproducibly deposited. The boron concentration for sample LRP 109 changes four orders of magnitude, from 10^{17} to 10^{21} atoms/cm^3, over a distance of less than 40 nm (10 nm/decade). For comparison, undoped/p^+/undoped multilayer structures deposited by MBE exhibit boron doping transitions of about 10 nm/decade.[2] These transition values are limited by the depth resolution of SIMS. Clearly, however, the p^+ multipulse sample shown in Fig. 1 demonstrates that LRP can produce ultrathin, highly doped films of epitaxial silicon with excellent control of layer thicknesses and doping profiles.

For electrical measurements, p^+ layers (0.1–0.6 μm) were deposited on n-type substrates. Figure 2 shows SIMS and spreading resistance data for sample LRP 82. The spreading resistance curve was scaled by matching its integrated carrier concentration to the value determined by Van der Pauw measurements. The Van der Pauw technique was also used to measure a sheet resistivity of 58 $\Omega/\square$ and a hole mobility of 42 cm^2/V s for sample LRP 82. This value of mobility is comparable to that of bulk material with the same hole concentration.[3]

By comparing the chemical concentration of dopant determined by SIMS with the hole concentration determined by spreading resistance, the degree of boron activation can be estimated. However, since the SIMS data are accurate only to about a factor of 2, the level of activation is difficult to determine. The highest hole concentrations measured by spreading resistance and Van der Pauw were in the range of 2×10^{20} cm^{-3}. For some samples, SIMS indicated significantly higher boron concentrations. Thus, inactive boron is probably present, the nature of which is currently being investigated. Previous transmission electron microscopy studies have shown boride particles in heavily doped p^+ bulk material.[4] Annealing experiments are being conducted to learn more about LRP boron incorporation and activation.

A dilute Schimmel etch[5] was used to characterize defect levels. Few defects ($< 10/\text{cm}^2$) were found for low-doped epitaxial layers deposited on p^+ substrates, while higher levels (about 3000/cm^2) were found for epitaxial layers deposited on n-type substrates. We are investigating this substrate dependence which may be caused by an internal gettering mechanism. In addition, some of the more heavily doped p^+ layers exhibited a very fine matte or slightly rough surface after defect etching which may be an indication of boride precipitates. It should be noted that these results were obtained without a clean room.

In summary, the fabrication of ultrathin regions of single crystal silicon with high doping densities and excellent electrical properties has been demonstrated using LRP. The ability to produce multilayer structures with sharp interface transitions suggests applications as diverse as those ascribed to MBE. We are currently exploring the use of LRP to fabricate devices based on multiple layers of semiconductors and insulators.

The authors appreciate the support of D. A. Reynolds and DARPA (contract no. DAAG29-85-K-0237), as well as the contributions of J. Hoyt, K. Lee of Bell Labs, C. Evans of Evans and Associates, the staff of the Stanford I. C. Lab, and Lockheed Corporation. C. Gronet acknowledges the support of an Office of Naval Research Fellowship.

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