A FIRST PRINCIPLES EXAMINATION OF THE DIFFUSION OF BORON IN SILICON DURING MICROWAVE RAPID THERMAL PROCESSING

K. Thompson, J.H. Booske, R.F. Cooper, C.J. Bonifas
University of Wisconsin, Madison
1415 Engineering Drive Madison, WI 53706

The rapid miniaturization of CMOS devices is rapidly outstripping our ability to develop processes that bring the necessary kinetic reactions to completion without detrimentally affecting other steps of the process flow. In ultra shallow junction (USJ) formation for the source/drain regions, the electrical activation of the implanted dopants, which must exceed 10^{20}/cm^3, requires a high temperature anneal step. Unfortunately, this high temperature process: enhances lateral diffusion, from the source/drain into the channel region; drives the implanted dopants deeper into the wafer, diluting their concentration; and degrades the integrity of novel high-k gate dielectrics. If CMOS scaling is to continue without a complete redesign of the gate structure, new processing techniques must be developed. Unfortunately, the present understanding of the physical mechanisms(s) controlling the reactions kinetics is far from robust.

We report on results obtained from studying the basic diffusion and activation mechanisms of microwave rapid thermal processing, RTP. For example, it is well known that both oxygen and fluorine affect the vertical diffusion of boron in silicon. What is not known, however, is the role these additional impurity species have on the diffusion of boron, the diffusion of each other, the diffusion of dopants in the presence or absence of high intensity optical illumination, or on the lateral diffusion of dopants. It has been reported by others that the presence of high intensity optical illumination alters the diffusion of impurities in silicon [1]. Microwave spike annealing provides insight into the reaction kinetics since it heats the wafer without optical phonon flux. Preliminary observations are that the effect of oxygen on boron diffusion is similar to lamp RTP [2] *only* when fluorine is present in the wafer in quantities on the order of the boron concentration, Fig. 1. For this case, decreasing the oxygen concentration in the ambient decreases boron diffusion. When fluorine is not present, Fig. 2, decreasing oxygen in the annealing ambient *increases* the boron diffusion, which is completely opposite the result seen in lamp-based RTP. A direct comparison, Fig. 3, shows the enhanced diffusion of boron during microwave spike RTP vs. lamp RTP when the oxygen concentration of the ambient is restricted to the very low concentration of 100 ppm. Note, however, that the enhanced diffusion in the microwave annealed sample can be a *beneficial* effect, since it promotes a near-ideal, box-like profile at a temperature at least 100°C lower than that required to produce the same profile and activation with lamp-RTP.

These experimental results were obtained during spike anneals to temperatures in excess of 900°C on a time scale of several seconds. Future generation CMOS devices, however, require a zero-net-diffusion re-crystallization process. This necessitates either a very low temperature (<700°C) anneal or a very high anneal temperature on a very short (milliseconds) time frame. During zero-diffusion RTP, the critical parameter of interest is the sheet resistance, Rs, obtained for a given thermal treatment. The activation of dopants during zero-diffusion microwave RTP (both low temperature and millisecond time frame) is discussed and compared to typical results from zero-diffusion lamp-based RTP. It is shown that low-temperature annealing must be analyzed carefully before making conclusions about dopant activation. In addition, general issues concerning the implementation of zero-diffusion microwave RTP (specifically on millisecond time frames) will be discussed.

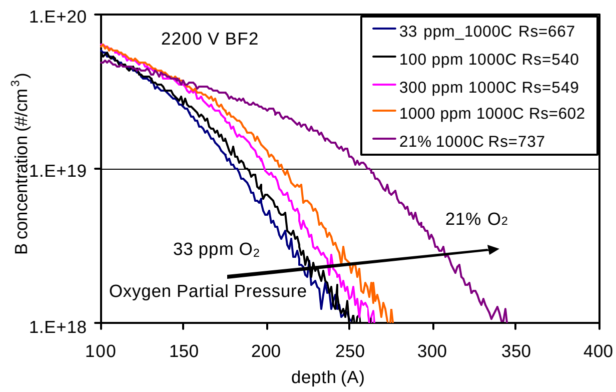

Fig. 1. Boron concentration profiles for a 10^{15}/cm^2 dose of BF_2 beam-line implanted at an energy of 2200 eV and microwave spike annealed to 1000°C in an ambient whose oxygen concentration [O_2] was varied as indicated in the legend. B diffusion increases with [O_2].

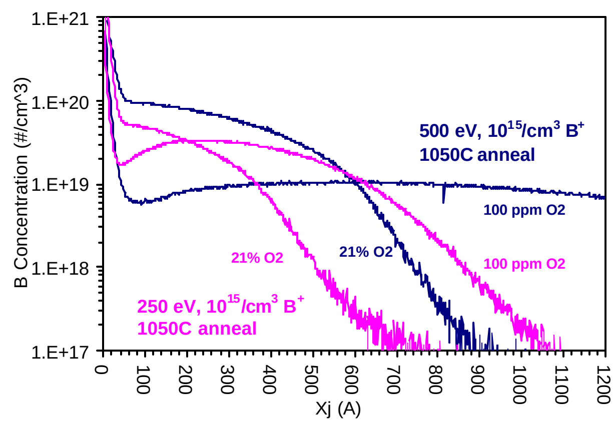

Fig. 2. Boron concentration profiles for two implant conditions: 10^{15}/cm^2 dose of B^+ at 500 eV and 250 eV; microwave spike annealed to 1050°C in an ambient whose oxygen concentration was varied as indicated in the figure.

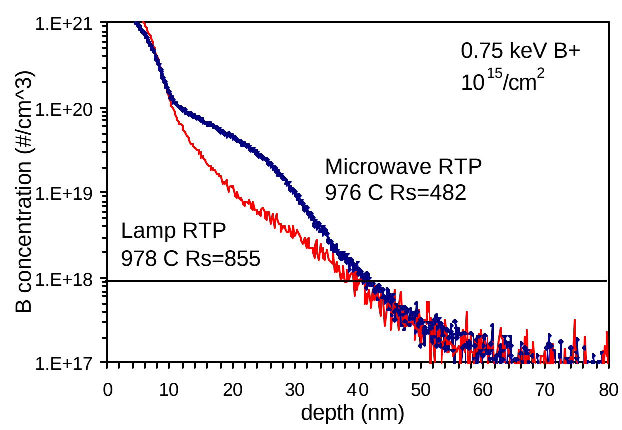

Fig. 3. Comparison study of microwave and lamp-based RTP for a 0.75 keV B+ beamline implant. A dramatic increase in near-surface lattice diffusion is seen for the microwave case.

1. R. Ditchfield, D. Llera-Rodriguez, E.G. Seebauer, Phys Rev-B **61**(20) p. 13710-20 (15 May 2000)
2. D.F. Downey, J.W. Chow, W. Lerch, J. Niess, S.D. Marcus, Proc. of the Materials Research Society (1999)