ELECTRICAL CONDUCTION IN
IMPLANTED POLYCRYSTALLINE SILICON

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Undoped polycrystalline silicon (poly-Si) films, 0.5 μm thick, have been prepared at 700°C by chemical vapor deposition (CVD) onto thermally oxidized n⁺-Si substrates. The impurity concentration was varied by implanting with As, P, and Sb ions, accelerated to 30 keV; total doses ranged from $2 \times 10^{11}$ to $3 \times 10^{15}$ ions/cm². Sheet resistance measurements, spanning 8 orders of magnitude, were made as a function of implantation dose. A reduction of 6 orders of magnitude in poly-Si sheet resistance took place within the implantation dose range between $10^{12}$ and $10^{14}$ ions/cm². Some samples also exhibited large reductions in sheet resistance following the standard heat treatment for Al contact sintering and surface state reduction, which is normally at 450°C for 0.5 hr in H₂. Sheet resistance measurements were also made as a function of temperature in the range 0 to 315°C. The effective activation energy for electrical conduction depends upon implantation dose. At low doses ($2 \times 10^{11}$ cm⁻²) the poly-Si is intrinsic, with $E_A = 0.65$ eV. At a dose of $10^{15}$ cm⁻², electrical conduction is a weak function of temperature, with $E_A = 0.027$ eV.

Key words: activation energy for electrical conduction, CVD polycrystalline silicon, hydrogen annealing, ion implantation, sheet resistance.
High-impedance load elements are finding increased utilization in silicon integrated circuits to reduce power consumption, thus permitting battery backup in non-volatile memory applications.\(^1\) Undoped polycrystalline silicon (poly-Si) appears to be potentially attractive for such applications, because its intrinsic high resistivity in the "as-deposited" state provides compact circuit layout. Furthermore, it has been suggested that load resistor current levels could be controlled over 4 orders of magnitude, from 0.1 nA to more than 1 µA, by means of ion implantation.\(^1\) In fact, the use of ion implantation to produce 30 MΩ \(\Omega\) poly-Si resistive elements to improve MOS memory performance has been reported.\(^2\) The controlled doping of poly-Si, which has been under investigation for more than 7 years, has been difficult, because the apparent free carrier concentration is only a fraction of the actual dopant concentration. Thus, for poly-Si films doped with boron during deposition, only 17% of the total 10\(^{17}\) cm\(^{-3}\) boron concentration yielded free holes.\(^3\) At lower doping levels, the discrepancy between doping concentration and free carrier concentration increases. Below 10\(^{16}\) cm\(^{-3}\) of P, the electron concentration is virtually intrinsic and independent of P-concentration.\(^4\) Even when impurity concentrations are known precisely by using ion implantation, average carrier concentration has been found to lag nearly 5 orders of magnitude below doping concentration in B-implanted poly-Si at the lowest dosage levels investigated (10\(^{12}\) cm\(^{-2}\)).\(^5\) In the dose range 10\(^{13}\) to 10\(^{15}\) cm\(^{-2}\), the sheet resistance of B-implanted poly-Si has been observed to drop 7 orders of magnitude.\(^6\)

Clearly the control of poly-Si sheet resistance during silicon integrated circuit processing requires extensive knowledge of the detailed mechanism of current transport, including diffusion and activation of the implanted species, poly-Si film morphology and grain structure as deposited, and possible structural transformation during subsequent processing. Most of the literature published on implanted poly-Si is limited to B ions, accelerated to 50 or 60 keV.\(^5,6,7\) One purpose of the present investigation was to extend observations to As, P and Sb ions, accelerated to 30 keV. In Section 2, an experimental structure is described that incorporates many of the processes actually utilized in MOS integrated circuit manufacture. The structure includes sintered Al contacts to the poly-Si and a poly-n\(^+\) substrate contact for ground return. Section 3 contains a summary of electrical measurements in which investigation spans more than 5 orders of magnitude in implantation dose, and the data are compared with unimplanted controls. Also included is an examination of the effects of annealing at 450°C in H\(_2\), which is generally required for ohmic contact formation\(^8\) and surface state reduction\(^9-11\) in MOS circuit manufacture. The final portion of Section 3 deals with empirical determinations of the activation energy for conduction in poly-Si, and how it depends upon implantation dose and H\(_2\) annealing. A discussion of the experimental data in terms of a theoretical model is contained in Section 4. The principal conclusions of this investigation are contained in the last section.