Impact of Ion Implantation Statistics on V_T Fluctuations in MOSFETs: Comparison between Decaborane and Boron Channel Implants

Hans Tuinhout, Frans Widdershoven, Peter Stolk, Jurriaan Schmitz,
Bert Dirks, Karel van der Tak, Pascal Bancken and Jarich Politiek

Philips Research Laboratories, Prof. Holstlaan 4, 5656 AA Eindhoven, The Netherlands

Abstract

MOSFETs with virtually identical doping profiles and DC behaviour exhibit significantly larger stochastic threshold voltage fluctuations when the channel is implanted using decaborane ($B_{10}H_{14}$) as compared to those with conventional boron implanted channels. This paper presents a unique experimental confirmation of the contribution of ion implantation statistics to V_T fluctuations.

Introduction

Random V_T fluctuations associated with stochastic dopant fluctuations can dominate V_T spread and can hence be a serious performance limitation for many VLSI circuit applications [1,2,3]. The theory for these fluctuations generally assumes Poisson statistics to describe the statistical nature of ion implantation processes [1,2,4]. Statistical simulations are used to verify the theory [4,5]. Statistical V_T mismatch measurements prove an excellent tool for studying stochastic fluctuations of microscopic device properties [1,3,4,6].

This paper presents the first direct experimental confirmation of the statistical nature of ion implantation processes. We report an increase of statistical V_T fluctuations due to enhanced dopant fluctuations when the channel region of a MOSFET is implanted using $B_{10}H_{14}$ as opposed to conventional B implanted channels. To explain the results, analytical models of V_T fluctuations as for instance discussed in [1,2,4] must include correlated dopant fluctuations.

TABLE I. IMPLANTATION DETAILS

	Low dose	High dose	Energy
Decaborane	1.7E11 cm^{-2}	3.5E11 cm^{-2}	180 keV
Boron	1.7E12 cm^{-2}	3.5E12 cm^{-2}	16 keV
Hydrogen	2.4E12 cm^{-2}	4.9E12 cm^{-2}	1.5 keV

Experiment

We compared twelve n-channel transistor types that were realised in an 'n-channel only' version of a 0.15 μm CMOS flow. Transistors with six different channel doping recipes ($B_{10}H_{14}$, B, or B with H, see Table I for doses) and two gate oxide thicknesses (4 and 6 nm) were evaluated. Implantation energies were chosen such as to yield similar projected ranges. The experiment was performed using a full suite of CMOS test modules including matching test structures [8]. On each wafer two transistor types (e.g. one with B and one with $B_{10}H_{14}$ channel implant) were realised by alternating use of the well masks. This enables undisputed comparison of two transistor types within each wafer, reducing effects of other disturbances. For this experiment the customary APT and the S/D halo implants were omitted to enhance effects of the channel implantation statistics.

Goto et al. reported the first application of $B_{10}H_{14}$ implants in CMOS technologies [7]. $B_{10}H_{14}^+$ ion cluster implantations have been performed using a home-made low-current, 750 kV implanter. To prevent premature decomposition of $B_{10}H_{14}$, the decaborane feed material was placed in a small cold-storage vessel connected with the argon gas supply. The mass selection is such that decaborane cluster fragments ($B_{10}H_{14-x}$) in the molecular-mass range 117 to 124 are implanted. All the implanted clusters contain ten B atoms each. A 90° magnet is used for mass separation and a switching magnet for the elimination of neutrals.

Stochastic V_T fluctuations were characterised by estimation of the standard deviation of the V_T mismatch between MOSFET pairs using a linear region 3-point extraction algorithm [8] on a high precision parametric measurement system (repeatability < 50 μV). The uncertainty in the measured statistical V_T fluctuation estimators is determined by the limited population size (≈60 to 250 pairs; max. 62 pairs per wafer-population).

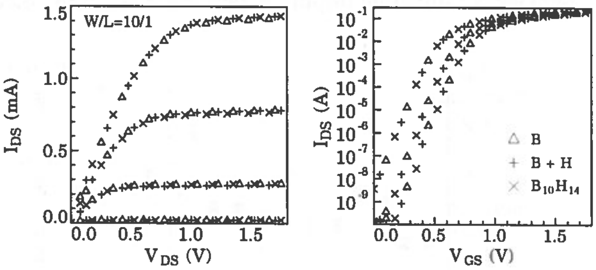

Fig. 1 Three groups of I-V characteristics for different transistors with the three different channel implants.

Results

MOSFET I-V's (Figure 1) and C-V measurements prove that the resulting doping profiles are virtually identical for devices made with $B_{10}H_{14}$ channel implants compared to those with B and B with H. This is supported by parametric measurements yielding V_{T0} differences of less then 10 mV, while body effect differences are negligible for comparable device types.

Fig. 2 presents V_T matching results. The dashed lines (slope = A_{VT}) represent the characteristic performance indicator for random V_T fluctuations of a particular device types in a particular technology [2,3,4,6]. Figure 2 shows a significantly larger mismatch A_{VT}-factor for the $B_{10}H_{14}$ type than for the B implanted channel. This is a clear indication that the stochastic fluctuation process underlying V_T mismatch is significantly stronger for the $B_{10}H_{14}$ implantation than for the B implants.

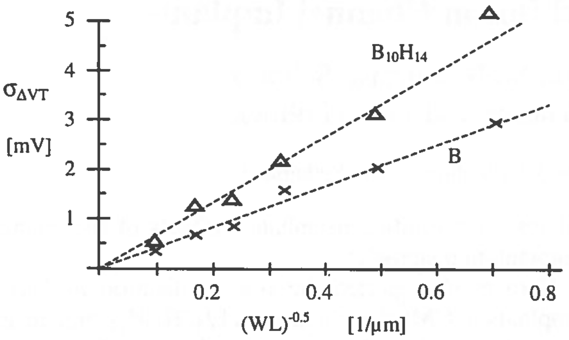

Fig. 2 V_T mismatch graph. $A_{VT,B10H14} \approx 6.5$, $A_{VT,B} \approx 4$ mVµm.

Furthermore it should be noted that the A_{VT}-factor for the standard B implanted devices (4 mVµm) represents the best matching performance published so far in the literature for this gate oxide thickness (granted the 'favourable' low channel doping in this experiment). This indicates that the devices are well constructed and that polysilicon gate morphology issues are well under control [6,9]. This is important as subtle dopant fluctuation effects would otherwise not be detectable!

Figure 3 summarises the mismatch standard deviations $\sigma_{\Delta VT}$ for the twelve transistor types. Figure 3 systematically reveals the following physical trends:

1. B implanted channels have equal matching performance as the B with H samples demonstrating that the co-implanted H has no impact on the matching.
2. $B_{10}H_{14}$ implanted channels yield significantly worse matching than B samples.
3. The expected linear dependence with T_{ox} as well as the (weak) substrate doping dependence are confirmed.

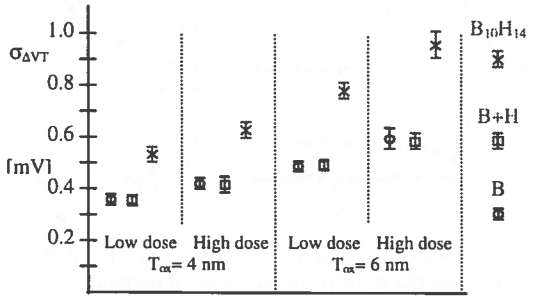

Fig. 3 $\sigma_{\Delta VT}$ for the twelve transistor types (W/L=10/10 µm).

Discussion

The results presented so far form clear experimental evidence that statistical fluctuations are significantly enhanced, when the channel dopants are implanted ten-by-ten. Since Poisson statistics is involved one would intuitively expect a $\sqrt{10}$ larger A_{VT} for the $B_{10}H_{14}$ samples. That this is not the case can be due to many reasons. Besides dopant number fluctuations (with and without correlations), there are several other mismatch sources that are not determined by the channel implantation such as the contribution of the number fluctuations of the implanted B well dopants, interface states and measurement noise (and statistical uncertainty).

However, it can also be shown on pure theoretical grounds that the extent to which the factor of $\sqrt{10}$ is reached depends on the exact doping profile. To model the ion cluster induced V_T fluctuation enhancement, the analytical approach that was presented earlier in [4] must be extended to describe correlated stochastic dopant fluctuations. Without proving the full derivation we give the extensions to equations (18) and (19) of [4] as:

$$\overline{\delta N_A(y)\,\delta N_A(y')} = \frac{1}{WL}\left(N_A(y)\,\delta(y-y') + \frac{Z-1}{D_B^{DB}} N_A^{DB}(y)\, N_A^{DB}(y') \right)$$

$$\sigma_{N_I} = \sqrt{\frac{1}{WL}\left(\int_0^{Y_d} (1-y/Y_d)^2 N_A(y)\,dy + \frac{Z-1}{D_B^{DB}} \left(\int_0^{Y_d} (1-y/Y_d) N_A^{DB}(y)\,dy \right)^2 \right)}$$

in which N_A and N_A^{DB} are the total B concentration and the B concentration due to the $B_{10}H_{14}$ implant, respectively, Z is the number of B atoms in a $B_{10}H_{14}$ molecule (i.e. 10), and D_B^{DB} is the total dose of B atoms due to the $B_{10}H_{14}$ implant. This result is substituted in (24) of [4] to calculate $\sigma_{\Delta VT} = \sqrt{2}\sigma_{VT}$.

Verification

To verify and visualise the results we compared the fluctuation enhancements as predicted by the model with measured V_T fluctuations as a function of the substrate bias. To reduce the influence of most of the mentioned other fluctuation sources, we assume that these additional factors are the same for a conventional B type population as for the $B_{10}H_{14}$ type on the same wafer. We define fluctuation enhancement (FE) as:

$$FE = 0.5\,WL\,(\,\sigma^2_{\Delta VT,DB}(V_{BS}) - \sigma^2_{\Delta VT,B+H}(V_{BS})\,)$$

$\sigma^2_{\Delta VT,DB}(V_{BS})$ and $\sigma^2_{\Delta VT,B+H}(V_{BS})$ are the measured mismatch standard deviations as a function of the substrate bias V_{BS} for the $B_{10}H_{14}$ and B+H types respectively. The results are depicted in figure 4. The model agrees very well qualitatively and reasonably well quantitatively. This demonstrates that the model properly describes the impact of correlated dopant fluctuations on stochastic V_T fluctuations.

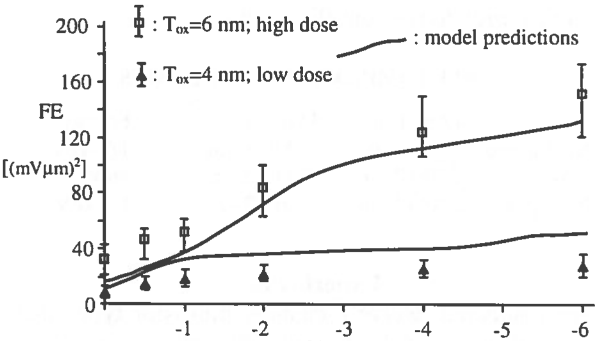

Fig. 4. V_T fluctuation enhancement verification.

Conclusion

We present the first direct experimental demonstration of the contribution of ion implantation statistics to V_T fluctuations, a major limitation for future VLSI processes.

References

[1] Laksmikumar et al. IEEE J.Solid-State Circ., vol.21, 1986
[2] Mizuno et al. IEEE Tr. El. Dev., vol.41, pp 2216-21, 1994
[3] Pelgrom et al in IEDM Tech. Dig., pp. 915-918, 1998
[4] Stolk et al., IEEE Tr. El. Dev., vol.45, pp. 1960-71, 1998
[5] Asenov, IEEE Tr. El. Dev., vol.46, pp 2505-2513, 1998
[6] Tuinhout et al, in IEDM Tech. Dig., pp. 631-634, 1997
[7] Goto et al, in IEDM Tech. Dig., pp. 435-439, 1996
[8] Tuinhout, to be published in ICMTS Tech. Dig., 2000
[9] Schmitz et al, in ESSDERC Tech. Dig., pp.156-159, 1999