

Modeling of Carrier Mobility Against Carrier Concentration in Arsenic-, Phosphorus-, and Boron-Doped Silicon

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Abstract—New carrier mobility data for both arsenic- and boron-doped silicon are presented in the high doping range. The data definitely show that the electron mobility in As-doped silicon is significantly lower than in P-doped silicon for carrier concentrations higher than 10^{19} cm^{-3} . By integrating these data with those previously published, empirical relationships able to model the carrier mobility against carrier concentration in the whole experimental range examined to date (about eight decades in concentration) for As-, P-, and B-doped silicon are derived. Different parameters in the expression for the n-type dopants provide differentiation between the electron mobility in As- and in P-doped silicon. Finally, it is shown that these new expressions, once implemented in the SUPREM II process simulator, lead to reduced errors in the simulation of the sheet resistance values.

I. INTRODUCTION

THE CAPABILITY to predict the sheet resistance is an important task of the process modeling programs; among other things, it permits the estimation of the source and drain resistances which are a limiting factor in the performances of MOS devices in VLSI technology [1]. It has been recognized that the primary limitation in the accuracy of simulated sheet resistance calculations is the availability of reliable mobility data and models [2]. As a matter of fact, a large spread (20–25 percent) [3] exists in the early mobility values reported in the literature, and the widely used process simulator SUPREM II [4] still includes several of the old mobility data of Irvin [5], which, in certain doping ranges, cannot be considered very accurate [6]–[8].

Recently, however, extensive measurements of carrier mobility on phosphorus-doped silicon have been made in our laboratory for electron concentrations n varying between 10^{18} and $4 \times 10^{20} \text{ cm}^{-3}$ [6] and at the National Bureau of Standards (NBS) in the range 10^{13} to $9 \times 10^{19} \text{ cm}^{-3}$ [7], [8]; these results are in good agreement in the overlapping range. Moreover, in [6] and [7] empirical relationships between the electron mobility μ_n and the carrier concentration have also been reported; the proposed formulae give a good fitting in the measured ranges of n , but, as the authors themselves claim, rapidly diverge for n greater than about $3.5 \times 10^{20} \text{ cm}^{-3}$ [6] and $2 \times 10^{20} \text{ cm}^{-3}$ [7], [8], respectively.

Very recently, other new mobility data, which extend the range of n covered up to $5 \times 10^{21} \text{ cm}^{-3}$ in P-doped silicon [9]

and which refer to $1.5 \times 10^{20} < n < 4 \times 10^{21} \text{ cm}^{-3}$ in As-doped silicon [10], have been presented; the carrier-concentration values higher than the solid solubility limits have been obtained by laser annealing techniques. These data show that in the examined range the carrier mobility in the As-doped films is lower than in the P-doped ones, in agreement with early observations [11], [12]. Therefore, it seems useful, from an engineering point of view: 1) to determine the carrier-concentration range in which the electron mobility in As-doped silicon significantly differs from that in P-doped silicon; 2) to derive simple expressions for the mobility against carrier concentration valid in the whole experimental range examined to date.

In this paper new carrier mobility data in As-doped silicon covering the 1×10^{19} – $1 \times 10^{20} \text{ cm}^{-3}$ carrier-concentration range are presented. Furthermore, for both As- and P-doped silicon an empirical relationship able to model these data and those recently published in [6]–[10] is derived. This new expression holds in the n range 10^{13} to $5 \times 10^{21} \text{ cm}^{-3}$ and clearly evidences, for the first time, the quantitative difference between the mobility of electrons in As- and P-doped silicon for n higher than about 10^{19} cm^{-3} . It is shown that its implementation in the program SUPREM II gives rise, for both P- and As-doped layers, to better agreement between the experimental and the simulated sheet resistance values.

Finally, a similar expression is derived for the modeling of the carrier mobility in B-doped silicon in the hole concentration range 10^{14} – $1.2 \times 10^{21} \text{ cm}^{-3}$; this has been accomplished by supplementing the NBS data for boron [8], [13] with new measurements for $5 \times 10^{19} < p < 1.2 \times 10^{21} \text{ cm}^{-3}$.

II. EXPERIMENTAL

Arsenic and boron atoms with doses varying between 2.5×10^{16} and $5 \times 10^{16} \text{ cm}^{-2}$ and from 1×10^{16} to $4 \times 10^{16} \text{ cm}^{-2}$, respectively, were randomly implanted into silicon substrates at an energy of 100 keV. The wafers were (100) oriented, $1 \Omega \cdot \text{cm}$ in resistivity, and of a conductivity type chosen to form a p-n junction. The arsenic-doped samples were annealed in a furnace at 1050°C for times ranging between 30 min and 9 h. Conversely, the dopant in B-doped samples was activated by a pulsed ruby laser with an energy of 1.9 J/cm^2 ; by this technique it was possible to completely activate the dopant and then to achieve supersaturated silicon layers with carrier concentrations higher than $1 \times 10^{21} \text{ cm}^{-3}$ [14].

It is worth noting that the electrically inactive dopant does

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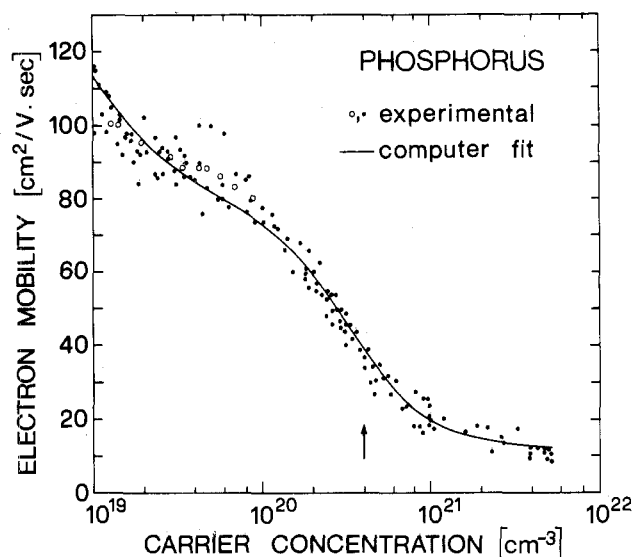


Fig. 1. Electron mobility as a function of electron density in phosphorus-doped silicon. Dots represent our data [6], [9], while open circles refer to data at 300 K reported in [8]. The arrow shows the solid solubility limit at 1100°C [23]. The continuous line represents the computer fit obtained with (1) and the parameters of Table I.

not affect the carrier mobility, which depends only on carrier concentration. In fact, the inactive dopant is present in the form of precipitates [21], [22] which give rise to a negligible carrier scattering with respect to the ionized impurity scattering. This has been shown for both P- [6], [9] and As-doped silicon [10], [15]. Even if experimental evidence of this effect has not yet been reported for B-doped silicon, it is reasonable to think that it holds in this case too; our measurements, however, refer to conditions in which hole density and boron density were about the same.

Carrier concentration and mobility profiles were measured at room temperature with the incremental sheet resistance and Hall-effect technique, by using a fully automated apparatus [16]. More details on the equipment used and on the measuring procedure are reported in our previous paper [6]. The ratio between the Hall mobility and the carrier mobility was set equal to 0.8, as assumed in [13], for hole density determination, while for electron density determination it was taken as equal to 1, according to the values measured on silicon samples heavily doped with phosphorus during crystal growth [17].

III. RESULTS

A. Phosphorus-Doped Silicon

Measurements of the electron mobility in silicon samples doped with phosphorus have been extensively performed in recent years in our laboratory [6], [9]. Fig. 1 shows a collection of these mobility data against carrier concentration in the range 1×10^{19} – 5×10^{21} cm⁻³; the data for n up to the solid solubility limit (about 4×10^{20} cm⁻³ at 1100°C [23]) were measured on thermally diffused samples [6], while those for higher values of n were measured on laser annealed samples [9]. It is worth noting that the data recently obtained by researchers of the NBS at 300 K [7], [8], and reported as open circles in Fig. 1, are in good agreement with our results.

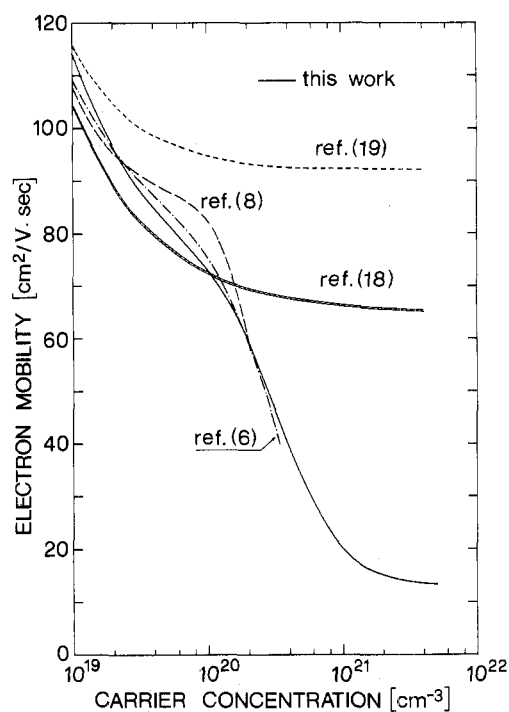


Fig. 2. Comparison between several empirical modelings of the electron mobility versus carrier concentration in P-doped silicon.

From Fig. 1 it clearly appears that μ_n is a continuously decreasing function of n ; as a consequence, simple formulae exhibiting a “min-max” behavior [18], [19] cannot account for the experimentally observed $\mu_n(n)$ behavior. Unfortunately, even the relationships recently suggested by Masetti and Solmi [6] and by Thurber *et al.* [7], which satisfactorily fit the data up to 3.5×10^{20} and 2×10^{20} cm⁻³, respectively, cannot be used at very high values of n because they rapidly diverge. All the above expressions are reported in Fig. 2 for carrier concentrations higher than 10^{19} cm⁻³ together with the fit obtained in this work and discussed below.

Taking into account the above observations, it seemed interesting to determine a single expression which, without discontinuities, can fit the μ_n versus n behavior. We found that the simple relationship

$$\mu_n = \mu_0 + \frac{\mu_{\max} - \mu_0}{1 + (n/C_r)^\alpha} - \frac{\mu_1}{1 + (C_s/n)^\beta} \quad (1)$$

can be satisfactorily used as an empirical model for a wide range of carrier concentration (10^{13} – 5×10^{21} cm⁻³). The first two terms in (1) give a “min-max” behavior of μ_n like those presented in [18], [19], while the third one, which is negligible for n lower than 5×10^{19} cm⁻³, accounts for the decreasing of μ_n at the highest values of n . Therefore, first we determine the four parameters μ_0 , μ_{\max} , C_r , and α by using a fitting procedure based on the accurate data recently reported by the NBS in the range 10^{13} – 9×10^{19} cm⁻³ [8] and on our data for n up to 1×10^{20} cm⁻³. The fitting was made by minimizing the rms relative error

$$\epsilon = \sqrt{\frac{1}{N} \sum_{i=0}^N \left(\frac{\mu_i - \mu'_i}{\mu_i} \right)^2} \quad (2)$$

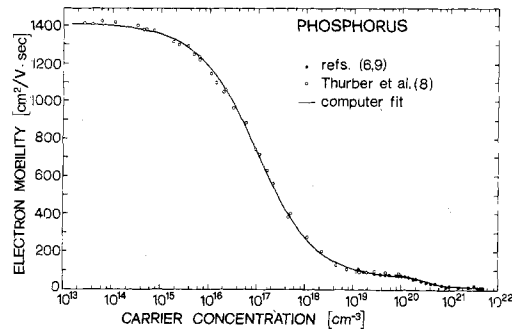


Fig. 3. Electron mobility against carrier concentration in phosphorus-doped silicon. The continuous line represents the computer fit obtained with (1). For sake of clarity, only a few of the available experimental data are reported for n higher than $1 \times 10^{19} \text{ cm}^{-3}$.

TABLE I
PARAMETERS FOR THE FIT USING (1) AND (4) OF THE CARRIER MOBILITY AGAINST CARRIER CONCENTRATION

	Arsenic	Phosphorus	Boron
μ_0	52.2	68.5	44.9
μ_{\max}	1417	1414	470.5
μ_1	43.4	56.1	29.0
C_r	9.68×10^{16}	9.20×10^{16}	2.23×10^{17}
C_s	3.43×10^{20}	3.41×10^{20}	6.10×10^{20}
α	0.680	0.711	0.719
β	2.00	1.98	2.00
p_c	--	--	9.23×10^{16}

where μ_i represents the experimental value and μ'_i is the calculated value given in this case by the sum of the first two terms in (1), pertaining to the i th measurement. Then, a similar fitting procedure was applied to the data reported in Fig. 1 for values of n higher than 10^{20} cm^{-3} to determine the remaining parameters μ_1 , C_s , and β .

Relationship (1), with the values of the parameters reported in Table I, is shown as a continuous line in Figs. 1 and 2 and is reported in Fig. 3 for the whole 10^{13} – 5×10^{21} carrier concentration range. Notice that the fitting obtained with (1) is practically coincident with that of the NBS [7] for n up to about 10^{19} cm^{-3} ; while some differences can be observed around 10^{20} cm^{-3} , where, due to the different formulae of fitting adopted, [7] tends to slightly overestimate the data while our fitting tends to slightly underestimate the data (see Fig. 2).

B. Arsenic-Doped Silicon

Generally no distinction was made in the past between the electron mobility in As- and in P-doped silicon; thus only limited data have been presented for As-doped silicon in recent years [10], [15], [20], [24]. The electron mobilities measured in this work for n between 1×10^{19} and $1 \times 10^{20} \text{ cm}^{-3}$ and those found in our previous study [10] for n higher than $1.5 \times 10^{20} \text{ cm}^{-3}$ are shown in Fig. 4 against carrier concentration. Some data taken from [15], [20] are also shown for comparison, but they are not used for the computer fit. Notice

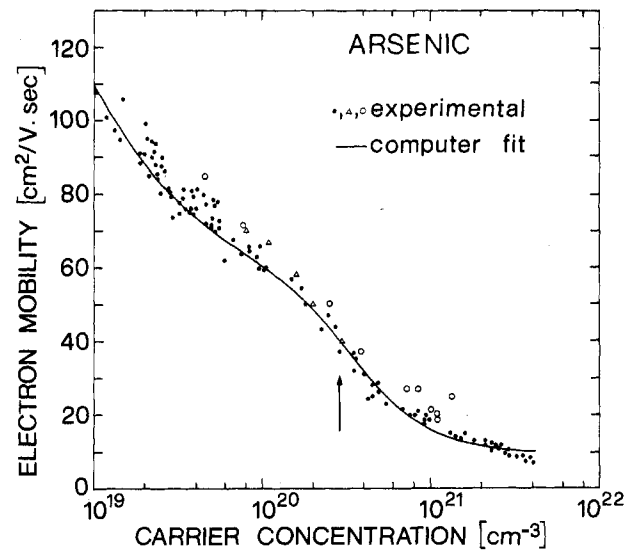


Fig. 4. Electron mobility versus carrier concentration in As-doped silicon. (●) our data; (○) data from [15]; (Δ) data from [20]. The arrow shows the solid solubility limit at 1050°C [10]. The continuous line represents the computer fit obtained with (1) and the parameters listed in Table I.

that our data [10] for n higher than the solid solubility limit (about $2.7 \times 10^{20} \text{ cm}^{-3}$ at 1050°C [10]) and those in [15] refer to laser annealed samples; all other data are for thermally annealed specimens. As can be seen, even in the case of As-doped films, μ_n is a continuously decreasing function of n . A comparison between the data reported in Fig. 1 and those reported in Fig. 4 indicates that the electron mobility in the As-doped samples is lower than the P-doped ones and that the mobilities for the two dopants tend to merge for values of n below about 10^{19} cm^{-3} . As a consequence, in our fitting we assumed that for n lower than 10^{19} cm^{-3} the mobility data recently reported in [7], [8] for P-doped silicon also hold for As-doped silicon.

We found that (1) can be successfully used to fit the μ_n data in As-doped silicon in the whole carrier-concentration range 10^{13} – $4 \times 10^{21} \text{ cm}^{-3}$. The corresponding fitting parameters, obtained with the same procedure described in the previous section, are reported in Table I and the resulting curve is shown as a continuous line in Fig. 4. The computer fit shows that the difference between the mobility in As- and P-doped samples monotonically increases from 6 percent at $n = 10^{19} \text{ cm}^{-3}$ up to 32 percent for $n = 4 \times 10^{21} \text{ cm}^{-3}$. For n lower than 10^{19} cm^{-3} , the two computer fits tend to merge and become practically coincident for n below $5 \times 10^{18} \text{ cm}^{-3}$.

C. Boron-Doped Silicon

Reliable hole mobility data are available in boron-doped silicon for hole concentrations p up to 10^{20} cm^{-3} [8], [13], but to the best of our knowledge no data are available for higher values of p . Fig. 5 shows the hole mobility values measured for this work in boron-doped samples for carrier concentrations in the range 5×10^{19} – $1.2 \times 10^{21} \text{ cm}^{-3}$ together with those recently reported by Thurber *et al.* at 300 K [8], [13]. The latter data are in good agreement with ours in the comparable hole density range. It clearly appears that

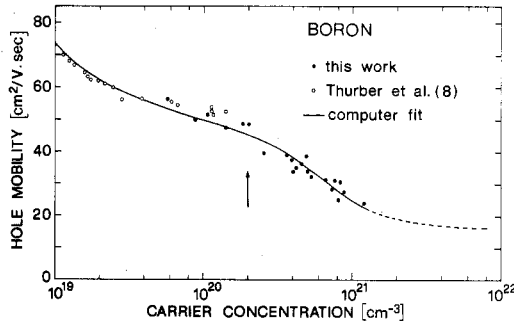


Fig. 5. Hole mobility against hole concentration in boron-doped silicon. The continuous line represents the computer fit obtained with (4) and the parameters of Table I. The arrow shows the solid solubility limit at 1100°C [25].

in B-doped silicon, the carrier mobility μ_p is a continuously decreasing function of the carrier concentration, similarly to As- and P-doped silicon.

It is shown in [13] that the μ_p against p behavior can be fitted, in the 10^{14} – 10^{20} cm^{-3} carrier-concentration range, by the expression

$$\mu_p = Ae^{-p_c/p} + \frac{\mu_{\max}}{1 + (p/p_{\text{ref}})^\alpha} \quad (3)$$

For high values of p (3) tends to the constant mobility value $\mu_p = A$; therefore it cannot account for the observed experimental $\mu_p(p)$ behavior for p higher than 10^{20} cm^{-3} . We found that the tail in the $\mu_p(p)$ behavior at high p values, can be satisfactorily modeled in the same manner we previously showed for As- and P-doped silicon, that is by simply subtracting a suitable increasing function of p from the relationship which fits the data in the low and intermediate concentration range. As a consequence, for boron-doped silicon the fitting relationship was taken as

$$\mu_p = \mu_0 e^{-p_c/p} + \frac{\mu_{\max}}{1 + (p/C_r)^\alpha} - \frac{\mu_1}{1 + (C_s/p)^\beta} \quad (4)$$

where μ_0 and C_r have the same meaning of A and p_{ref} in (3). After choosing for μ_0 , μ_{\max} , C_r , α , and p_c the values at 300 K reported in [13], the other parameters μ_1 , C_s , and β were determined with the best-fitting procedure on our data. (4), with the values of the parameters reported in Table I, is shown as a continuous line in Fig. 5.

IV. DISCUSSION

The difference, observed at high carrier-concentration values, between the electron mobility in As- and in P-doped silicon samples can give rise to significant differences in the sheet resistance of As- and P-doped layers. MOS VLSI technologies preferentially use arsenic as the dopant for the source and drain regions because its diffusion coefficient is lower than that of P and consequently shallower junction depths can be obtained. However, the higher sheet resistance of the arsenic layers could create some problems in high-speed circuits. In any case, for accurate process modeling, the different $\mu_n(n)$ behavior in As- and in P-doped silicon has to be taken into account.

Actually, SUPREM II does not make any difference between

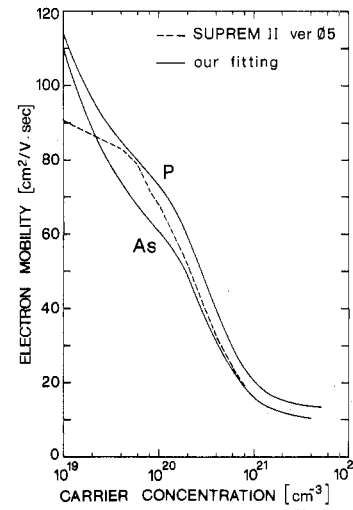


Fig. 6. Electron mobility versus carrier concentration. The dotted line represents values used in SUPREM II [4] for both As and P, while the continuous lines represent our modeling.

the electron mobility in As- and in P-doped silicon. Mobility data are available in SUPREM II in a tabular form [4]. For concentrations in the range 2×10^{15} – 6×10^{19} cm^{-3} the old data of Irvin [5] are used; for 8×10^{19} – 4×10^{20} cm^{-3} the points determined by Michel and Guerin in As-doped samples [4] are adopted; while in the ranges 1×10^{14} – 1×10^{15} cm^{-3} and 6×10^{20} – 1×10^{21} cm^{-3} an extrapolation is made. Fig. 6 shows, for high concentrations, a comparison between our fitting for the As and P dopants and the data available in SUPREM II. As can be seen, the μ_n data available in SUPREM II are sometimes closer to the μ_n values in As-doped silicon and sometimes closer to the μ_n values in P-doped silicon; moreover, electron mobilities available in SUPREM II are appreciably lower than our values for n around 1×10^{19} cm^{-3} .

The fitting relationships presented in this work have been implemented in SUPREM II.¹ An example of the results is reported in Table II, where experimental and simulated sheet resistance values (obtained with both our mobility modeling and the SUPREM II versus 0.5 mobility modeling) are compared. The data refer to arsenic and phosphorus atoms with a dose of 7×10^{15} cm^{-2} ion implanted in silicon through 60 nm of silicon dioxide, at an energy of 150 and 70 keV, respectively. The samples were then thermally annealed in nitrogen at 1000°C for 3 and 30 min. As can be seen, by using our relationship the percentage errors in the simulated values of the sheet resistance are reduced.

Finally, in Fig. 7 we report, for carrier concentrations higher than 1×10^{18} cm^{-3} , the resistivity against carrier concentration as achievable from (1) and (4), for arsenic-, phosphorus-, and boron-doped silicon. Apart from the previously observed difference between As- and P-doped silicon, it appears that at the highest concentrations the most conductive silicon layers are those doped with boron. The cross point in resis-

¹Notice that, as our mobility expressions are function of the carrier density, care must be taken when a significant compensation arises, that is when dopants of different type and with comparable concentration are present.

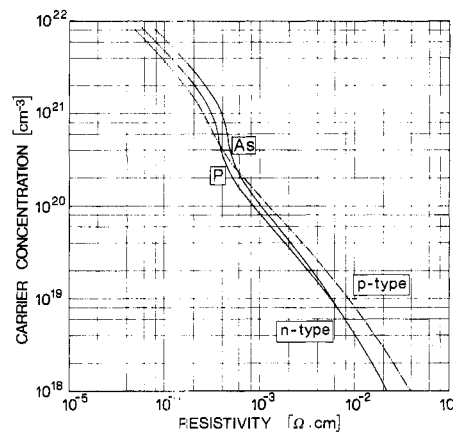


Fig. 7. Carrier concentration against resistivity for silicon doped with arsenic, phosphorus, or boron. The results have been obtained by using (1) and (4) for the carrier mobility modeling.

TABLE II
COMPARISON BETWEEN EXPERIMENTAL AND SIMULATED SHEET
RESISTANCE

(Simulated values were obtained with the use of (1) and with the data present in SUPREM II versus 05, respectively.)

Dopant	Annealing time (min)	Experimental	Modified SUPREM II		SUPREM II vers 05	
		ρ_s (ohm/□)	ρ_s (ohm/□)	error (%)	ρ_s (ohm/□)	error (%)
AS	3	52.0	44.1	15.2	41.5	20.2
	30	28.7	29.1	1.4	27.2	5.2
P	3	25.1	28.8	14.7	32.5	29.5
	30	15.6	16.4	5.1	17.8	14.1

tivity between As- and B-doped silicon is located at a concentration around $2 \times 10^{20} \text{ cm}^{-3}$, while that between P- and B-doped silicon is located around $4 \times 10^{20} \text{ cm}^{-3}$.

V. SUMMARY AND CONCLUSIONS

In this paper we have presented new data for the carrier mobility in both arsenic- and boron-doped silicon in the high carrier-concentration range. These data together with those recently obtained in our laboratory [6], [9], [10] definitely show that:

- 1) The electron mobility in arsenic-doped silicon is lower than in phosphorus-doped silicon for n higher than about 10^{19} cm^{-3} ;
- 2) For arsenic-, phosphorus-, and boron-doped silicon, the carrier mobility continuously decreases as the carrier concentration increases, even for carrier densities one order of magnitude higher than the solid solubility.

Furthermore, we have presented simple empirical relationships which accurately model the experimentally observed carrier mobility in As-, P-, and B-doped silicon over a wide range of carrier concentrations (10^{13} – $5 \times 10^{21} \text{ cm}^{-3}$ for phosphorus, 10^{13} – $4 \times 10^{21} \text{ cm}^{-3}$ for arsenic, and 10^{14} – $1.2 \times 10^{21} \text{ cm}^{-3}$ for boron).

Finally, the above expressions have been implemented in SUPREM II, which previously did not differentiate between the mobility in As- and in P-doped silicon. We have found that with the adoption of our modeling of the carrier mobility, the SUPREM II estimated sheet resistance of implanted-diffused layers is in better agreement with the experimental results.

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A Theory of Noise in GaAs FET Microwave Oscillators and Its Experimental Verification

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Abstract—A theory has been developed which provides an entirely analytical approach to the calculation of AM and FM noise in free-running GaAs FET microwave oscillators. The theory is based on the model that low-frequency device noise is mixed with the carrier signal via the nonlinearity of the FET and upconverted to microwave frequencies. Because of the analytical nature of the theory, all the important device and circuit parameters on which the noise generation depends are explicitly given.

Two GaAs FET oscillators have been fabricated and used to investi-

gate the FM noise. The theory predicts well both the spectral dependence and the absolute magnitude of the FM noise in both oscillators. The noise performance of the oscillators differs by 19 dB. The theory indicates that no single factor is responsible for this, and moreover that attention should be given to the optimization of many device and circuit features in the design of a low noise FET oscillator.

I. INTRODUCTION

IN RECENT years it has been demonstrated that GaAs FET's can be used to produce high-efficiency microwave oscillators [1]-[7]. Power outputs of 40 to 100 mW, for 300- μ gate widths, have been fairly commonly achieved in X band [3]-[7], and oscillators have been shown capable of

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