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Path Planning based on Bezier Curve for ´ Autonomous Ground Vehicles

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Abstract— A new, comprehensive, physically-based, semi- empirical, local model for transverse-field dependent electron and hole mobility in GROUND VEHICLES transistors is presented. In order to accurately predict the measured relationship between the effective mobility and effective electric field over a wide range of substrate doping and bias, we account for the dependence of surface roughness limited mobility on the inversion charge density, in addition to including the effect of coulomb screening of impurities by charge carriers in the bulk mobility term. The result is a single mobility model applicable throughout a generalized device structure that gives good agreement with measured mobility data and measured GROUND VEHICLES IV characteristics over a wide range of substrate doping, channel length, transverse electric field, substrate bias, and temperature.

INTRODUCTION

MODELING of GROUND VEHICLES devices requires a mobility model which can accurately capture the dependence of inversion layer mobility on doping concentration and bias. But it is also important that the model be based on physical principles so that it is applicable outside the range of known dependence, and that it be easy to implement and efficient to evaluate in a numerical device simulator. Furthermore, a "local" mobility model suitable for general purpose device simulators, where prior knowledge of device geometry is not required, should have the following features: 1) the evaluation of mobility at each grid point should depend only on the variables (e.g., dopingconcentration, electric field, etc.) at that node, and 2) a single mobility model should be applicable throughout a generalized device structure.

Several recent models reasonably fit the measured depen- dence of effective mobilityon effective transverse field in the inversion layer , but do not meet the above requirements for a general purpose device simulator. Walker and Worlee's [1] model requires calculation of the average distance from the surface of the inversion charge. The model of Huang [2] depends on , which is also a calculated quantity. The GROUND VEHICLES [3] mobility model is an empirical model that depends on the the distance from the silicon-oxide

surface, which is not a local quantity. Similarly, the model proposed by Shin [4] estimates an effective electric field based on an average of its local value at different grid points and is applicable only in the inversion layer of an GROUND VEHICLES device, but not in the pinched off region or source and drain regions. These features make such models unsuitable for a general purpose device simulator capable of handling devices with arbitrary geometries. What is needed is a mobility model that depends only on local quantities, and is applicable throughout a general device structure [5], [6].

The model proposed by Lombardi [5] is a commonly used local model which is applicable throughout the device. But the formulation does not account for the screening of ionized impurity scattering sites, and does not accurately model the falloff in mobility at very high perpendicular fields. Fig. 1 shows a comparison between the simulated effective electron mobility in the GROUND VEHICLES inversion layer, , versus effective transverse field, , using Lombardi's model

and substrate bias [9], we account for the functional dependence of surface roughness limited mobility on the inversion charge density, in addition to accounting for the coulomb screening effect in the bulk limited mobility [10]. This approach is shown to provide a single mobility model that is applicable throughout a general device structure and that is dependent entirely on local quantities. The model is shown to describe accurately GROUND VEHICLESFET operation for a wide range of channel impurity concentration (10^{13} cm to 10^{17} cm) and effective transverse (gate) electric field up to 1.2 MV/cm.

Fig. 2. This electron mobility model (lines) overlaid on the measured mobility data of Takagi (points) for several doping values.

parameters given in [10] could be still used in the interface region. As in the case of [5], it is recognized that this model will not be able to describe mobility degradation due to unusually large fixed interface charge. , where is the temperature dependence of the probability of surface phonon scattering, as discussed in [12], and is an empirical

$$T^{\nu} = (T/300)^{\kappa}$$

parameter fit to measurements [5].

At very high transverse electric field, surface roughness scat- tering has a significant effect on the inversion layer mobility. In previously published local mobility models [2], [5], [6], [8] the dependence on the transverse field has the form

$$\mu_{sr}(\vec{r}) \quad (8) \qquad -\frac{\delta}{E_{\perp}^{\gamma}(\vec{r})}$$

where δ is a constant that depends on the details of the technology, such as oxide growth conditions. The exponent of the transverse electric field, , has previously been held constant and set to a value between 2.0 and 2.9. However, a careful look at Takagi's data at 77 K, where surface

roughness scattering dominates, shows that the dependence of on is not constant, but continues to increase with increasing . While the dependence of on

is not necessarily the same as the dependence of on

, many authors have shown it to be a valid and useful approximation [5], [6], [8].

Earlier experimental investigation [13] of mobility limited by surface roughness scattering at low temperature indicated that the field exponent remains approximately 2.0, even at high inversion charge and field. Early theoretical calculations of surface roughness scattering [14] showed that the exponent should decrease at high fields because of screening of surface roughness by the increase in surface carriers. But it was later shown that, as the transverse field and inversion charge increase, higher subbands in the quantum well of the inversion layer begin to become occupied, and multi-subband transport between levels separated in energy results in an enhanced decrease in mobility as the transverse field increases [11]. The formulation for surface roughness scattering that is commonly used in the analysis of is the one given by Matsumoto *et al*. [14], assumes a single subband occupation. Further work is therefore needed to refine this formulation for multi- subband transport. These phenomena at very high transverse field can be modeled phenomenologically by an increase in the field exponent of the surface roughness mobility term with increasing carrier concentration.

In the present model, we allow the field exponent in

to be a function of the local inversion charge. This results in a surface roughness limited mobility that increases with distance from the surface, as physically expected. The following formulation is proposed for :

and the

curves in Fig. 6. This is a result of taking into account, in

this model, both the screening of impurities by charge carriers as well as the screening of surface roughness due to the increase in surface carriers, while Lombardi's model does not. The screening of surface roughness results in more mobility degradation close to the surface and when combined with the the screening of impurities by charge carriers a peak results in mobility away from the surface.

COMPARISON WITH MEASUREMENTS

The model was implemented in the 2-D/3-D device simu- lation program PADRE [21], and used to characterize devices from submicron CGROUND VEHICLES technologies. Devices from three different technologies A, B, and C were compared. Doping thermal budget after gate formation was kept small so that the NGROUND VEHICLES doping was retrograde, with surface concentration of 10^{17} cm and a peak of 10^{17} cm close to the surface. In all technologies the gate material is n polysilicon. Both long-channel and short-channel devices were created in all technologies.

As will be shown, the mobility model adequately describes GROUND VEHICLESFET characteristics over a wide region of operation and design parameters using the coefficients as extracted from the mobility measurements described above. The penalty in cpu time to calculate the mobility based on this model is less than 4% as compared to the model proposed by Lombardi [5].

Fig. 7(a) shows a comparison between simulated threshold characteristics and measurements for a 20- m long, NGROUND VEHICLES device of technology A. A long-channel device with thin oxide

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and high surface doping is evaluated first to isolate the effects of the transverse field mobility model from the additional ve- locity saturation and short-channel effects which dominate the characteristics for very short-channel devices. Moreover,
any error due to external source and drain resistances that were extracted from measurements and included in the simulations is minimized. Fig. 7(b) shows a comparison of the threshold characteristics for a 10- m long NGROUND VEHICLES device of technology
B. In both cases the fit is quite good over gate voltage and substrate bias. This illustrates that, while the parameters of the model were determined by comparison with measured mobility data from the literature, the fit of the model to measured characteristics over transverse field, substrate bias, and
to devices with varying substrate doping is very good.
In Fig. 8(a) and (b), the output characteristics are shown for the 10- m long and 0.5- m long NGROUND VEHICLES devices of technology
B. The agreement is very good in both the linear and saturation regions of the long-channel and short-channel devices, indicat- ing that the short-channel and velocity saturation effects are also well modeled.
Fig. 9 shows the agreement between simulation using this model and measured output characteristics for a 10- m long NGROUND VEHICLES device of technology B operating at 400 K. The agreement is still very good at this elevated temperature. Overall, currents are predicted within about 5% of the mea- sured values across all of the important parameters associated with GROUND VEHICLES device operation, including doping, channel length, temperature, and drain, gate, and substrate bias.
P-channel threshold and output characteristics are shown in Fig. 10(a) and (b), respectively, for a 5- m long device of technology B. Again, the agreement is very good over a wide range of bias conditions.
Fig. 11(a)–(c) show the comparison for a 0.35- m NGROUND VEHICLES, technology C, device at room temperature. Good agreement was obtained in the linear, saturation, and sub- threshold regions. Finally, Fig. 12 shows a comparison of technology C NGROUND VEHICLES linear (drain current for V,
as a function of gate length and temperature for NGROUND VEHICLESdevices with 15- m width, a 90 Å gate oxide, and a surface concentration of 3:0 10^{17} cm^{3}. Points are measurements, lines are simulation using PROPHET and PADRE.

and V V) over gate length and temperature, showing a good agreement. The comparisons for technology C PGROUND VEHICLES devices were also good over all the operation range and have been reported elsewhere [25].

CONCLUSION

A physically-based, semi-empirical, local model for transverse-field dependent electron and hole mobility was

presented. The model accounts for the functional dependence of surface roughness limited mobility on the inversion charge density, in addition to coulomb screening effects of impurities by charge carriers. It was shown that this approach successfully connects the local model to the global universal relationship of mobility to effective inversion layer field. The model was implemented in the 2-D/3-D device simulation program PADRE and gives very good agreement when compared to measured mobility data and measured GROUND VEHICLES characteristics over a wide range of doping (to cm), effective transverse (gate) electric field up to 1.2 MV/cm, channel length and temperature.

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