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Theory of Hot Electrons and Saturation Velocities in Silicon Inversion Layers

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Since the operating condition of MOS LSI is in a region of high source drain field, the transconductance of each MOS transistor is limited by high electric field saturation velocity rather than low field mobility of carriers in surface inversion layers. Although measurements of the saturation velocity of electrons in Si inversion layers have been performed by several authors,[1] the mechanism which determines the value of the saturation velocity is not clear at present. Recently, Katayama et al. have observed a differential negative resistance effect in an n-type inversion layer of a Si MOS field effect transistor in high source drain field at low temperatures.[2] They have indicated that the effect is a result of hot electron phenomenon in a two dimensional subband structure formed in the inversion layer by strong gate field.

In this paper, we investigate theoretically the hot electron problem in Si inversion layers with the principal objective of elucidating the mechanism which leads to the velocity saturation and the negative resistance effect. The model takes into account the two dimensional subband structure and related change in scattering rates. The scattering of electrons due to ionized impurities at the interface of oxide and semiconductor, surface modes of lattice vibrations and surface irregularities are taken into consideration. In each subband, the scattering rates due to these mechanisms have relatively weak dependence on the energy of the electron except the ionized impurity scattering reflecting the constant density of states of the two dimensional subband. In the high energy region, inter-subband scattering and intervalley or optical phonon scattering which result in large energy change become important.

Energy distribution functions of the electrons are calculated as a function of source drain field and gate field by the method of diffusion equation in energy space[3] in warm electron region and by the Monte-Carlo method[4] in high source drain field. The electrons are heated by the source drain field and develop their energy distribution into high energy region within the same subband initially, extend the distribution into higher subbands, and finally experience the intervalley or the optical phonon scattering and change their energy in a large amount by emission of a corresponding phonon. At liquid helium temperarures where the ionized impurity scattering is the dominant mechanism which limits the mobility of the low energy electrons, the electrons are easily heated into the high energy region where they are scattered strongly by the intervalley or the optical phonons. At higher temperatures, the electron heating occurs more slowly because of the energy loss to intravalley acoustic phonons but final limitation by the intervalley or the optical phonons are equally effective as in the low temperature case.

Drift velocities of the electrons calculated from the above distribution functions show the saturation behavior in high source drain field at temperatures above 10K. The saturation velocities are determined mainly by the energy of an appropriate intervalley or optical phonon characteristic of the surface orientation but have additional temperature dependence due to the intravalley acoustic phonon contribution which is larger in two dimensional case than the bulk case.

At liquid helium temperature, the energy distribution function deviates strongly from the Maxwellian shape even in the warm electron region which results in a peculiar dependence of the electron temperature on the electric field.[1)] The differential negative resistance is obtained in sufficiently high source drain fields which has the following characteristic features:

1) The negative resistance is obtained at high gate field where the two dimensional subbands are well established.

2) It is observed irrespective of surface orientation. Inversion layers in $\langle 111 \rangle$ and $\langle 110 \rangle$ surfaces give the negative resistance as well as $\langle 100 \rangle$ surfaces.

3) It appears at temperatures where the ionized impurity scattering is dominant in the low energy region.

These features are consistent with the experimental results.

References

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