1-1 *INVITED*: CHARACTERISTICS OF THE TRANSFERRED ELECTRON EFFECT

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Several compound semiconductors, GaAs, InP, CdTe and some alloys, exhibit the transferred electron effect in which electron scattering to states of low mobility in high electric fields leads to a negative differential conductivity of the bulk semiconductor. The effect is exploited in microwave oscillators and amplifiers; at the present time GaAs devices are in widespread use and InP devices are under development in the laboratory. The theoretical study of the transferred electron effect has two main aspects. The first is to analyse the basic characteristics of the effect, in particular the properties of the instabilities that arise under high field conditions and the modes of operation of devices. The second aspect is to consider the relative advantages of different semiconductors. A major theoretical difficulty is the slow response of the electrons throughout most of the electric field range where negative differential conductivity is exhibited. Consequently an understanding of the devices requires account to be taken of the dynamic response of the electrons as well as their behaviour under steady conditions.

Within the approximations implicit in a semiclassical description of electron motion, the behaviour of the electrons is determined by calculating their distribution function. Before 1966 the methods used for calculating distribution functions involved approximate analytic solution of the Boltzmann equation. These gave a useful insight into some basic features of the transferred electron effect, but lacked the power to deal realistically with the behaviour of devices. Since 1966 several numerical methods have been developed which can be applied, in principle, to problems of arbitrary complexity, including those where the electron system varies in time and space. Their application to the transferred electron effect has greatly improved the understanding of the physics of the effect and of the characteristics of devices.

Three phases of the development of the subject can be identified. The first concentrated on the behaviour of electrons under steady conditions; the main objective was to calculate the static velocity-field curve. A topic of particular interest is the dependence of the peak to valley ratio of the velocity-field curve, which directly relates to the limiting device efficiency, on the material parameters of the semiconductor. A prediction of a high maximum efficiency for InP devices, in which material a distinctive 3-level transfer mechanism was proposed, is an example.

The second and third phases concentrated on the detailed device characteristics, particularly their frequency limitations. The second phase followed naturally from the recognition of the importance of electron relaxation processes at microwave frequencies. While still treating the electron system as spatially uniform, it was shown that the effective negative differential conductivity of the electrons degrades with increasing frequency. A limiting oscillation frequency for GaAs devices of about 100 GHz was predicted. In addition effects of electron reactance become important at high frequencies and the interpretation of the microwave conductivity of a device in terms of a velocity-field curve needs appropriate correction.

The characteristic of the third development phase is the removal of the restriction of spatial uniformity, which allows the electron relaxation process to be included in device simulations. Previous simulations had given useful information regarding the properties of instabilities and the operation of devices, but neglect of relaxation processes had introduced several unrealistic features. The inclusion of the relaxation processes has led to a reappraisal of the properties of accumulation layer and dipole domain instabilities, particularly their nucleation characteristics and their velocities, and of the modes of operation and frequency limitations of devices. As an example the frequency limit for a GaAs lsa oscillator is now estimated to be about 25 GHz. A feature of this phase of the work is the analysis, for the first time, of relaxation effects that become important as the device length is reduced. Major deviations from a simple picture are predicted for devices shorter than 10 microns, in particular an increased oscillator efficiency can result from a change of cathode type from an n^+ to a current limiting contact.

A discussion will be given of recent work on the modes and characteristics of oscillators and amplifiers, the differences between GaAs and InP and the experimental information relating to these areas of research.