Two-Dimensional Modelling of Non-Stationary Effects in Short Gate Length GaAs MESFET's

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ABSTRACT

A two-dimensional non-stationary simulation is described which has been used to model short gate length (<0.5μm) GaAs MESFET's. Energy and momentum relaxation effects are taken into account by rigourous numerical solution of the full set of semi-classical transport equations. The two-dimensional variation of electron energy in thin channel short gate length MESFET's is demonstrated and the influence of hot electrons penetrating the substrate/buffer layers of MESFET's is investigated.

1. INTRODUCTION

The drive towards higher operating frequencies has led to the development of microwave devices with very short active channels. In the case of MESFET's, gate lengths of less than 0.5μm are required in many applications including monolithic integrated circuits. Present commercial devices already gate lengths of less than 0.3μm and laboratory devices with 0.1μm gate lengths are being developed. The carrier transport mechanisms in short devices with active lengths of less than 1μm do not obey the equilibrium conditions found in longer devices. In particular, electron transport in the high field regions in the proximity of the Schottky barrier gate in MESFET's with short active channels, is strongly influenced by

non-stationary effects, notably velocity overshoot.

Classical analyses, which assume equilibrium transport conditions, proceed by solving Poisson's equation in association with current continuity equation(s). Analytical techniques based on closed-form solutions have been shown to be inadequate for modelling FET operation for devices with gate lengths of less than 1μm and many physical models based on numerical solutions have been developed to simulate microwave MESFETs [1,2,3,4]. It has been established that in short gate length devices, non-equilibrium effects, such as velocity overshoot, are significant and hence device models should take these effects into account. A full non-stationary model requires the solution of four non-linear coupled partial differential equations - Poisson, current continuity, energy and momentum continuity equations. Several attempts have been made at solving this system and useful quasi-two-dimensional energy transport models have been reported [5,6,7,8]. Comprehensive two-dimensional hot-electron models have been slow to emerge because of the difficulty in obtaining convergent stable solutions for the full set of transport equations, and because of the requirement for extensive computer resources. Frequently the spatial variation of the electron energy is completely neglected. This assumption is shown here to lead to substantial errors for devices with gate lengths of the order of 0.3μm or less. The results presented here demonstrate that for MESFET's with short gate lengths and thin active channels, the energy distribution of electrons in the device is clearly two-dimensional, and has a significant effect on the device characteristics.

Recently there has been considerable interest in solving the full two-dimensional energy and momentum conservation equations [6,9,10] and recent results confirm that this type of model characterises the device more accurately and than classical 'diffusion' and simplified energy transport models, with simulation results agreeing well with experimental data. The model described here has been used to characterise a number of MESFETs with gate lengths of less than 0.5μm.

The model described here allows the influence of substrate and buffer layers to be quantified. In particular, the effects of hot electrons penetrating the substrate in thin channel devices has been characterised. The criticallity of the doping and mobility profiles in relation to the performance of the MESFET is also assessed. The results are compared with experimental data for 0.3μm and 0.5μm gate length MESFET's.

2. SEMI-CLASSICAL DEVICE MODEL

A two-dimensional 'hydrodynamic' semi-classical model was used describe the operation of the device. This approach has been explored by several researchers [5,6,7,8,9,11] and has usually led to the development of simplified transport models based on electron temperature. The models are based on an approximation to the Boltzmann transport equation and assume a displaced Maxwellian distribution for the electrons. Although these approximations are not strictly valid for gallium arsenide, Blotekjaer [12] has shown that if the transport parameters are characterised in terms of the average velocity of the electrons in the centre valley, a set of useful transport equations can be extracted.

The model follows the classical approach of solving Poisson's equation to extract the potential distribution ψ and hence deduce electric field distribution.

$$\nabla^2\psi = \frac{q}{\epsilon_o\epsilon_r}(N_D - n) \quad (1)$$

where $\epsilon_o\epsilon_r$ is the dielectric permittivity of the material. The electric field $\vec{E}$ is obtained directly from the potential using the relationship,

$$\vec{E} = -\nabla\psi \quad (2)$$

The electron distribution is obtained from the solution of the current continuity equation:

$$\frac{\partial n}{\partial t} + \nabla.(n\vec{v}) = 0 \quad (3)$$

Equations (1),(2) and (3) constitute the classical semiconductor equations solved for the well known drift-diffusion model. Semi-classical transport equations are used to describe the non-equilibrium transport for electrons in the MESFET:

Momentum conservation

$$\vec{v} = \frac{\tau_m}{m^*}\left(q\vec{E} + \frac{2}{3}\nabla\xi + \frac{2\xi}{3n}\nabla n\right) \quad (4)$$

Energy conservation

$$\frac{\partial\xi}{\partial t} = q\vec{v}.\vec{E} - \vec{v}\nabla\xi - \frac{1}{n}\nabla(n\vec{v}kT_e) - \frac{\xi - \xi_o}{\tau_e(\xi)} \quad (5)$$

where n is the electron concentration, $\vec{v}$ the electron velocity, $\vec{E}$ electric field, q electronic charge, ξ average electron energy, ξ_o is the equilibrium energy, K Boltzmann's constant.

τ_m and τ_e are the momentum and energy relaxation times. The energy conservation equation expressed in equation (5) may be considered as having three components which constitute the energy balance in the device. The first term on the right hand side of equation (5) describes the electron heating effect due to the electric field, the second and third terms describe the energy flow through the device and the third term describes the energy loss due to collisions. The second term can also be expanded to incorporate a term due to diffusion of the energy through the device and is currently being investigated. It is the inclusion of this spatially dependent second term which causes the greatest difficulty in obtaining a stable solution and is often neglected in simplified models to yield the more commonly used form:

$$\frac{\partial \xi}{\partial t} = q\vec{E}.\vec{v} - \frac{\xi-\xi_o}{\tau_e(\xi)} \tag{6}$$

The mobility μ may defined as

$$\mu(\xi) = \frac{q\tau_m(\xi)}{m^*} \tag{7}$$

where μ is a function of average energy ξ and effective mass m^*. Results obtained using empirical mobility functions based on experimental data obtained from the low field mobility profiles for MESFET's is compared with results obtained using equation (6), later in the text. The velocity equation (2) can be conveniently re-expressed in terms of electron temperature T_e,

$$\vec{v} = \mu(\xi)\vec{E} + \left[\frac{K\mu(\xi)}{q}\nabla T_e + \frac{KT_e\mu(\xi)}{qn}\nabla n\right] \tag{8}$$

The first part of the expression on the right hand side of this equation is the drift term and the terms in brackets represent the diffusion term. The inclusion of a term for spatial variation in T_e (or ξ) indicates that the hottest electrons will diffuse out of the collection more rapidly. This may be important in devices where there is a large amount of electron heating such as in the vicinity of Schottky barriers. Curtice and Yun [5] have shown that if the temperature gradients are negligible, then this term may be omitted yielding an expression similar to the classical expression $\vec{v} = \mu\vec{E} + D\nabla n/n$. The results from the current work described below show that it is incorrect to assume negligible temperature gradients in short gate length MESFET's. A consequence of using the electron temperature model is that the diffusion term is assumed to be isotropic rather than anisotropic as predicted by Monte Carlo techniques.

The corresponding electron temperature expression for equation (5) is:

$$\frac{\partial T_e}{\partial t} = \frac{2}{3K} q \vec{v}. \vec{E} - \frac{5}{3}\vec{v}.\nabla T_e - \frac{1}{n} \nabla.(n\vec{v}\, kT_e) - \frac{T_e - T_o}{\tau_e(\xi)} \quad (9)$$

The electron temperature, relaxation times and mobility characteristics T_e, τ_e and $\mu(\xi)$ were obtained as a function of electric field E and average electron energy ξ using Monte Carlo models [9][11]. The electron temperature is expressed in terms of the difference in total electron energy ξ and the kinetic energy,

$$T_e = \frac{2\xi - mv^2}{3k} \quad (10)$$

The terminal currents i_s, i_d and i_g for the source drain and gate respectively were obtained by integrating the current density $\vec{J}$ across a suitable surfaces enclosing each contact,

$$I = \int_p \vec{J}\, ds \quad (11)$$

where

$$\vec{J} = qn\vec{v} + \epsilon_o \epsilon_r \frac{d\vec{E}}{dt} \quad (12)$$

3. MESFET MODEL

The model of the MESFET is based on a two-dimensional geometry of the form shown in Figure 1. In addition to the highly doped active layer both substrate and buffer layer regions may be included, with the appropriate doping profile. The model assumes a thermionic emission diffusion model for the Schottky barrier gate [4]. A simplified planar geometry was used for the majority of the models, reducing the solution domain to a rectangle. This approximation simplifies the computer coding and results in a subsequent saving in cpu time compared with the requirements for non-planar devices. Non-planar MESFET models have also been considered for recessed gate MESFETs using specially developed algorithms [13].

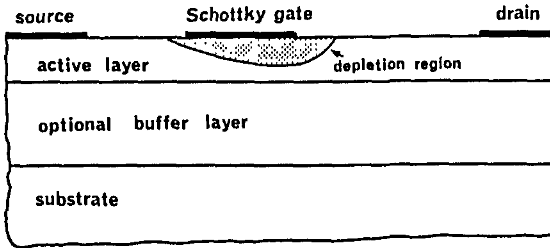

Figure 1. Two-Dimensional Planar MESFET Model.

4. Numerical Solution

Many earlier simulations were based on classical semiconductor equations (for example [2]), and frequently considered unrealistically low active channel doping levels because of restrictions in the numerical schemes and computing resources. Modelling of highly doped ($>2x10^{23}m^{-3}$) GaAs devices puts severe constraints on the stability, convergence and accuracy of the numerical schemes compared with silicon numerical models. The two-dimensional time-dependent semiconductor equations outlined previously were solved numerically using finite-difference schemes, which allow fast, flexible solution schemes which are easiliy encoded. There is very little detailed published information available on other numerical techniques suitable for solving the highly non-linear energy and momentum equations. The Poisson equation was solved using an over-relaxation iterative scheme. A modified Scharfetter-Gummel algorithm was used to solve the current and energy continuity equations, which ensured excellent numerical stability and accuracy in the vicinity of the the gate depletion region (particularly critical in highly doped devices). Dirichlet boundary conditions are used at the ohmic contacts. Free surfaces are assumed to have zero carrier and potential gradients normal to the surface, and are represented using truncated Newton-Gregory polynomials.

A variable mesh spacing may be used to optimise speed and accuracy of the solution. The time and space step widths are determined by both physical and numerical constraints. In order to achieve a physically meaningful solution the time step Δt is kept to less than the dielectric relaxation time and to avoid degrading the accuracy of the numerical solution Δt is usually kept to less than 25fs. The space steps are similarly restrained to a Debye length in the active channel and for

numerical stability it has been found that a step width of the order of 0.01 microns in the active channel is necessary. These limitations on the space stepwidths Δx and Δy are not critical in neutral regions of the device far away from the gate depletion region and advantage can be taken of larger step widths in these regions using a variable mesh.

5. MESFET CHARACTERISTICS

The geometry, doping profile and mobility profiles of the MESFETs can be arbitrarily specified. The model allows n^+ implants to be included for source and drain contacts. Several structure have been investigated, comparing fabricated devices with simulated results obtained from the model described above. The structures for 0.5μm and 0.3μm gate length MESFETs are shown in Figure 2. Several doping profiles have been investigated for the 0.3μm gate length device, Figure 2.

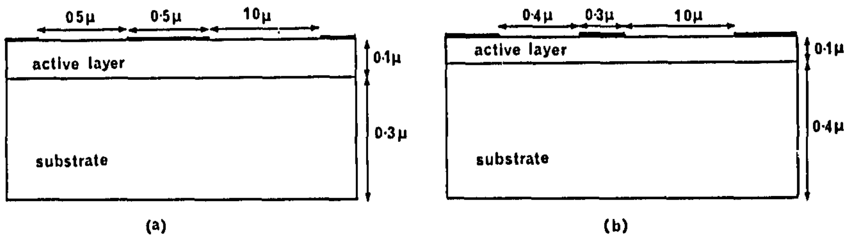

Figure 2. Cross-Sections of (a) 0.5μm and (b) 0.3μm gate length MESFET's.

5.1. Doping and Mobilty Profiles

Another consequence of the need for thin highly doped active channels in sub-micron MESFETs is that the doping profile of the device extending from the active layer into the buffer layer and/or substrate can strongly influence the behaviour of the device. Many device models neglect this effect and even assume an abrupt profile. The results presented below clearly demonstrate the importance of accounting for exact form of the doping profile in modelling the device, and that the commonly used assumption of an abrupt profile is not normally adequate. A useful measure of this effect is the comparison of d.c. characteristics of both simulated and measured MESFETs. It is apparant that substrate current may be significant in these devices.

The mobility profile also plays an important role in determining the drain to source incremental conductance and the pinch-off voltage. Average channel low field mobility measurements were carried out using an automated geometric magneto-resistance facility. Examples of measured profiles are shown in Figure 3. The field-dependent mobility was determined using a temperature dependent expression which incorporates the low field value [9]. This has been compared with theoretical values obtained using equation (6). It is important to appreciate that the experimental mobility profile can depart substantially from profiles obtained using relationships which relate the mobility to bulk doping densities, such as Hilsum's relationship [14]. Whilst this type of theoretical dependence can adequately model the mobility in the active channel, it frequently fails to represent the mobility in semi-insulating substrates, where the material characteristics depart from those of bulk n-type material, and indeed where the substrate can even be lightly p-type. This difference between the bulk low field mobility, often included in FET models, and the actual measured mobility profile may account for the unexpectedly high drain-source conductances and exaggerated pinch-off voltages predicted by earlier models.

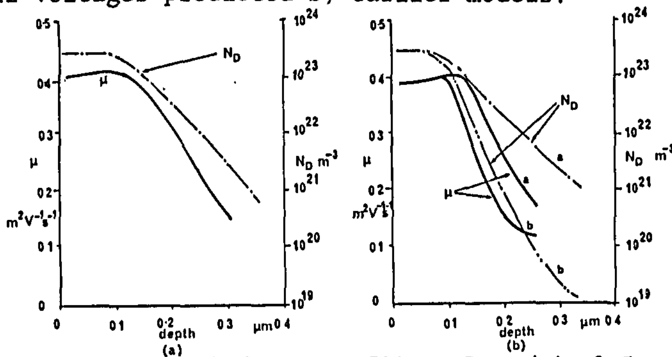

Figure 3. Measured Mobility Profiles for (a) 0.5μm and (b) 0.3μm gate length MESFET's.

5.2. Simulation Results

The static voltage current characteristics for the 0.3μm and 0.5μm gate length devices are shown in Figure 4. A comparison with results obtained from the classical drift-diffusion model of equations (1) to (3) and the simplified energy model of equation (6) are also included. It is immediately clear from these results that the form of the doping profile has a very strong influence over the characteristics of the FET. The non-stationary models predict

higher drain currents which are closer to the measured values than the drift-diffusion model. Furthermore, the inclusion of a detailed energy model is important to ensure accurate results in the shorter gate length devices. Examination of the carrier distributions shown in Figure 5 reveal that for MESFETs with thin active layers the majority of the channel current flows along the active layer/buffer layer or active layer/substrate interface. The current density distributions shown in Figure 6 reveal that there is also a substantial component of the total current flowing in the substrate. This is particularly significant in the case of the 0.3μm gate length device which has a 0.1μm thick active channel.

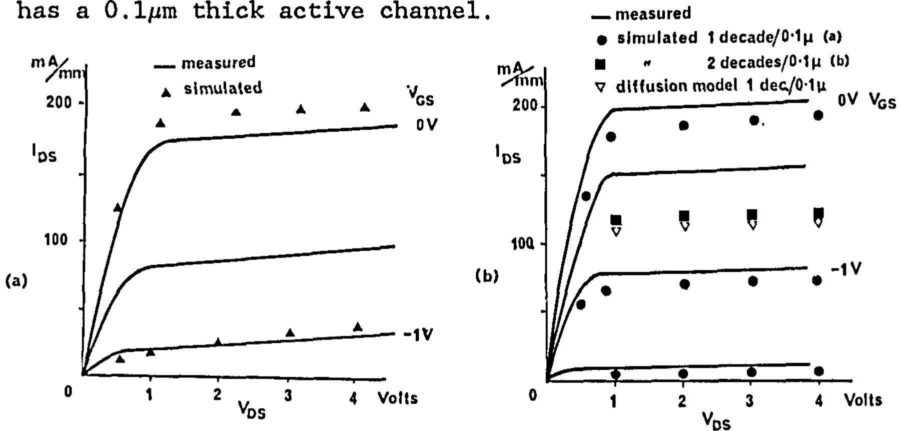

Figure 4. I-V Characteristics for (a) 0.5μm and (b) 0.3μm gate length MESFET.

The carrier distributions shown in Figure 5 also reveal that there is considerable penetration of the buffer layer/substrate by carriers and that a substantial substrate current flows in these devices. Furthermore, it is clear from the electron temperature distribution shown in Figure 6 that the electron energy has a highly two-dimensional distribution in these short gate length devices. This has a significant effect on the carrier distribution, causing an enhancement of the dipole region at the drain end of the gate and an extension of the channel depth under the gate.

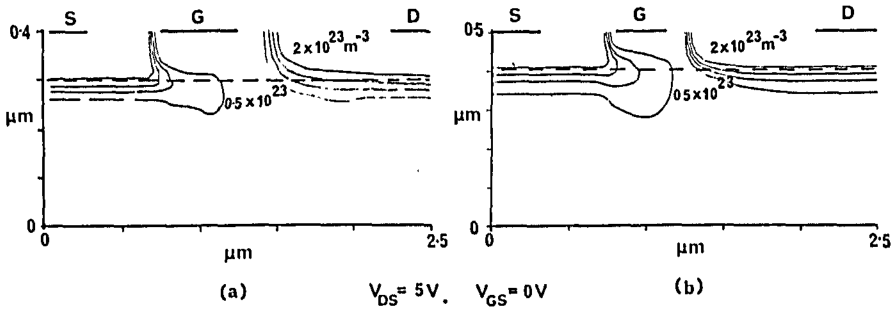

Figure 5. Electron Distributions in (a) $0.5\mu m$ and (b) $0.3\mu m$ gate length MESFET's.

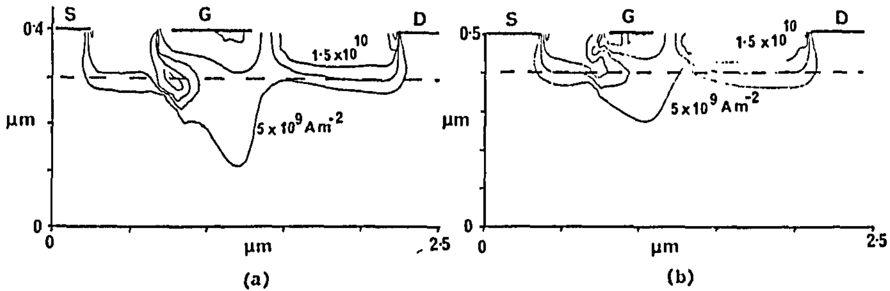

Figure 6. Longitudinal Current Density Distributions for (a) $0.5\mu m$ and (b) $0.3\mu m$ gate length MESFET's.

The effect of the non-stationary effects can be better understood by simultaneously comparing the carrier distribution, energy distribution and velocity profile of Figure 7 for the full energy model. Electrons in the channel under the source end of the gate have a relatively low energy and are confined to a narrow channel region. However, the electrons achieve a very high velocity, overshooting to a value in excess of $2.5\times10^{5}ms^{-1}$, preserving current continuity. Towards the drain end of the gate the electrons have obtained sufficient energy from the electric field to penetrate the substrate and deepen the effective channel. In this region the electron velocity decreases to a local minimum close to the point of maximum electron energy gradient where a large proportion of the electron current is due to the temperature gradient. In regions of the active channel where the gradient

of the electron temperature is significant, equation (8) predicts that there is a contribution to the electron current density. The electron temperature distribution of Figure 8 shows that this is most important in the channel under the middle of the gate, where ∇T_e reaches a maximum positive value, and in the region beyond the gate towards the drain where ∇T_e reaches a peak negative value. There is also a substantial electron temperature gradient below the drain end of the gate, normal to the channel direction penetrating the substrate to a depth of over 0.4μm. In regions of high temperature gradient it is found that the contribution of this term to the total current density exceeds 20% for the 0.3μm gate length MESFET.

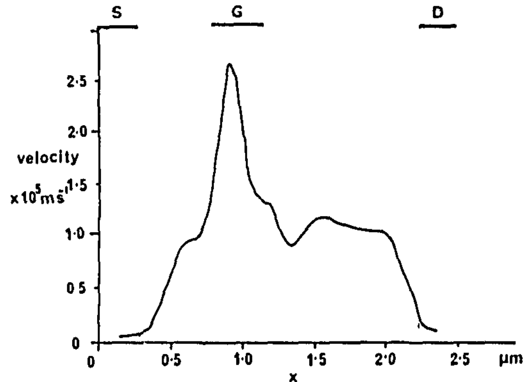

Figure 7. Velocity profile for electrons travelling along the active channel.

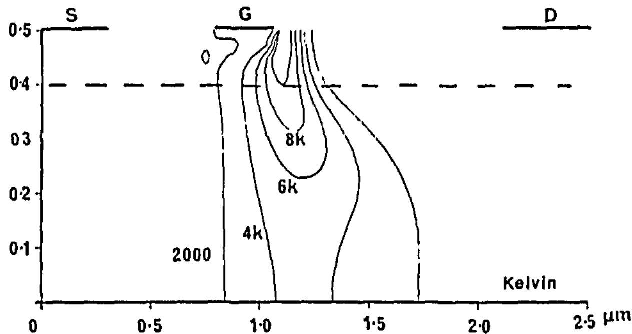

Figure 8. Electron Temperature Distribution for 0.3μm gate length MESFET.

The potential distributions shown in Figure 9 for the drift-diffusion, simple energy and full energy models show very little difference which tends to confirm that the the

difference in drain current is not predominantly caused by any difference in the electric field strengths.

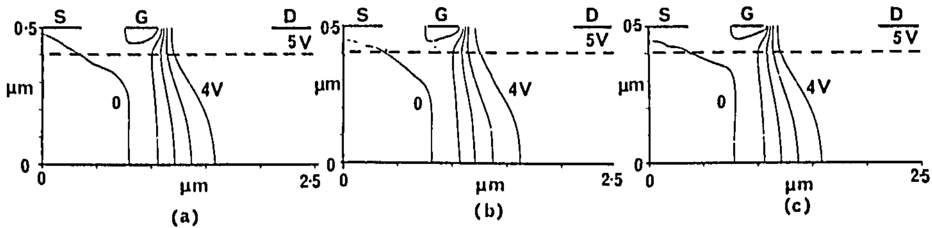

Figure 9. Potential Distributions for (a) drift-diffusion (b) simple energy and (c) full energy models.

It might be expected from these results that any apparent improvement in the transit time of the channel for the energy model compared with the drift model, due to the higher average electron velocity caused by velocity overshoot, would be compensated by an associated increase in the dipole capacitance due to the modified charge distribution under the drain end of the gate. Hence, there is only a small improvement in the predicted cut-off frequency f_T for the non-stationary model. It has been found that this small change is sufficient to account for the bulk of the difference between measured results and those predicted by drift-diffusion models.

The measured results for devices fabricated to the specification used in the simulation have been superimposed on the I_{DS}/V_{DS} characteristics. It is apparent that the agreement between the model and measurement is very good. Results obtained from diffusion-type models (without energy relaxation effects included) have been included for comparison. The f_T of 24 GHz predicted by the energy model for the 0.5μm gate length MESFET was 8% higher than of that of the measured chip device. The difference may be due to parasitic effects of the test fixture.

Conclusions

The simulations reveal that in short gate length, thin channel MESFETs, the spatial energy distribution appears to vary significantly and is strongly two-dimensional in nature.

This suggests that simplified models which do not account for this variation and assume either constant carrier energies or one-dimensional energy transport are not well suited for modelling sub-half micron geometries. Furthermore, the simulations confirm that a significant proportion of the electron current in short gate length devices is due to the electron temperature gradient.

The model clearly shows that the MESFET characteristics are very sensitive to doping density gradients at active layer/substrate and active layer/buffer layer interfaces in thin channel devices. Early results from two carrier models suggests that this effect is minimised by the use of p-type substrates. The mobility profile was also found to have a substancial effect on the drain conductance and pinch-off voltage.

Comparisons of results obtained from classical transport models (diffusion models), simple semi-classical models and the full semiclassical model implemented here show that the choice of model strongly effects the results obtained for short gate length MESFETs. It appears that to ensure an accurate model it is important to include a rigourous treatment of the energy conservation equation equation, such as the one reported here.

Acknowledgments

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