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FINAL REPORT

FORECASTING OF THE PERFORMANCE OF MOS DEVICE FOR SPACE APPLICATIONS

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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INTRODUCTION

In this report, two subjects are investigated:

I. Analysis of radiation damage of MOSFET data from Explorer XXXIV (IMP-F), and

II. Radiation damage characteristics of MOSFET with boron diffused between silicon semiconductor and silicon oxide.

The first subject is an interpretation of the discrepancy between the space data and the laboratory data. Accroding to the work of John L. Wolfgang, Jr.[1)] for an equal flurence, the space damage is less than the damage observed in the laboratory. Present work will establish a mathematical model based on which to calculate the accumulated damage especially when the radiation flux is not a constant, such as in the space orbit: a satellite would see the flux as a function of time. This result will be useful in the forecasting of the stability of MOSFET in radiation environment.

The second subject is an attempt to analyze the radiation damage characteristic of MOSFET when there is modification of the electrical property in gate oxide region. In such a system, the recent result of Vitaly Danchenko[2)] indicates a spontaneous recovery of the radiation damage. We will propose a mechanism for this recovery. A substantiation of a mechanism which leads to a spontaneous recovery in MOSFET would be very important to the design of MOSFET for future space applications.

(I) Radiation Damge of MOSFET in Space

We quote a summary of Wolfgang"

"After 60 orbits of IMP-F 9.5×10^{10} electrons/cm^2 (energy 0.55 Mev) dose has been received by the 0.25 gm/cm^2 shielded devices. The gate threshold shift of similar devices, at the same dose of 1.5 Mev electrons in laboratory studies, indicating possible minor annealing is occurring over the highly elliptical orbit in flight."

There are two problems in order to discuss this interesting observation: (1) can there be annealing at the temperature range of 10 to 20°C where the device experienced in IMP-F. The answer is affirmative, at least in the qualitative sense. A small annealing at a low temperature of 25°C is reported by Danchenko et al.[3)] with an observational period of 100 hours. This time range is close to the orbital period of IMP-F. Independently, we will also prove that the space data implies the existence of an annealing of MOSFET in space.

In the experiment of Wolfgang in the laboratory, the radiation time is in the order of minutes. To reach the same level of fluence in space will take several months. Therefore, our second problem is to investigate theoretically, by introducing explicitly the annealing effect, the radiation damage under these two condtions.

In the following, we will establish a kinetic equation for simultaneous radiation and annealing, and from this equation, we will discuss the observational results.

A kinetic equation describes the change of the defect concentrations of a system. In low level, moderately high energy radiation, such is the case under present investigation n is linearly proportional to the fluence Φ. Furthermore, we reploted the data of Wolfgang on the fluence dependence of the shift of gate threshold voltage ΔV_{GT}, instead of seim-log, in a regular graph, the result shows a straight line (Fig. 1), that is ΔV_{GT} is linearly proportional to Φ. Therefore,

V_{GT} is linearly proportional to n.

$$V_{GT} = 2.1 \times 10^{-9} \text{ mv}/(\text{e/cm}^2). \quad \text{In other words,} \tag{1}$$

ΔV_{GT} is related to n by a constant multiplier k, i.e.,

$$\Delta V_{GT} = kn \tag{1'}$$

In our treatment, therefore, we can simply discuss the conventional variable n of the kinetic equation, instead of the complex quantity, ΔV_{GT}.

If n_o denotes the accumulated concentration of defects, in our case, as we have already discussed, n_o is linearly proportional to the total fluence of the radiation,

$$n_o = \alpha \text{ (proportionately constant)} \cdot \Phi \text{(the fluence)}. \tag{2}$$

Now, if n anneals according to the usual first order kinetics, at time t after the radiation,

$$n(t) = n_o e^{-t/\tau} \qquad (3)$$

where τ is the recovery (decay of defects) rate.
In the space, since the radiation and the recovery are simultaneous, therefore,

$$\frac{dn}{dt} = \frac{-n}{\tau} + \alpha\phi \qquad (4)$$

where ϕ is the flux rate. For constant flux rate, $\phi = \frac{\Phi}{t}$. Therefore, starting with zero damage, after a time t,

$$\begin{aligned} n &= \alpha\tau\phi(1-e^{-t/\tau}) \\ &= n_o \frac{\tau}{t} (1-e^{-t/\tau}) \end{aligned} \qquad (5)$$

The result of Eq. (3) is obviously different from that of Eq. (5) unless in the limiting case where t approaches zero. The result of Eq. (4) is based on an assumption that ϕ is a constant, independent of the time. We now treat the case that ϕ is a periodic function of time and to be concrete, in the form

$$\phi = A\sin^2\omega t \qquad (6)$$

This form of flux function has been applied by Dr. R. Waddel in his analysis of solar cell radiation damage for a series of Relays and ATS satellites and found a good agreement.[4)]
In the case of Explorer, the spacecraft is in the radiation belt for only 4 hours orbit, i.e. about $\frac{1}{25}$ of an orbit. Eq. (6) will represent a better approximation than the constant flux treatment of Eq. (5). From Eq. (6), after one period, we can calculate A of Eq. (6) by a comparison

with the fluence Φ:

$$\Phi = \int_{o}^{\pi/\omega} A\sin^2\omega t$$

$$= \frac{A\pi}{2\omega} \tag{7}$$

The integration of Eq. (4), now becomes,

$$n = ce^{-t/\tau} + \alpha\Phi\frac{\omega\tau}{\pi}\left[1 - \frac{\cos 2\omega t + 2\omega\tau\sin 2\omega t}{1 + 4\,\omega^2\tau^2}\right] \tag{8}$$

where α is the defect production rate. Since the unit of integration constant c in Eq.(8) and α are unspecified so far, according to Eq. (1'), n of Eq.(8) can be replaced by ΔV_{GT} which, for simplicity, will be denoted by V.

At t = o, i.e., before irradiation, V = o, from which the integration constant c can be determined and the integration from o to π/ω gives,

$$V_1 = \frac{\alpha\Phi}{s}(1-x)(1-y), \tag{9}$$

where the abbreviation symbols are, $s = \pi/\omega\tau$, $x = (1 + 4\,\omega^2\tau^2)^{-1}$, $y = e^{-s}$. Now, in the laboratory experiment, radiation time is negligible, therefore Eq. (2) becomes,

$$V_1' = \alpha\Phi y, \tag{10}$$

where the superscript (') of V denotes the laboratory radiation value of V. From Eqs. (9) and (10),

$$\frac{V_1'}{V_1} = s(1 + \frac{s}{4!^2})/(e^s-1) \tag{11}$$

By a series expansion, the righthand side of Eq. (11)

becomes,

$$\left(1 + \frac{s^2}{4\pi^2}\right)/\left(1 + \frac{s}{2} + \frac{s^2}{6} + \frac{s^3}{24} + \ldots\right),$$

The coefficient of s^2 in numerator, $(\frac{1}{4\pi^2})$, is smaller than that of denominator, $(\frac{1}{6})$, and all other terms in the denominator is positive, therefore,

$$\frac{V_1'}{V_1} > 1. \tag{12}$$

This result is opposite to the observation of Wolfgang.

The above investigation is based on the result of a single orbit. A practical problem is to investigate the resultant damage after a satellite is passed through the radiation belt many times.

From Eq. (8), for the second orbit, at t = o, V will have the value V_1 given by Eq. (9). At the end of second period, we find, from the same model of calculation,

$$V_2 = \frac{\alpha f}{s}(1-x)(1-y^2). \tag{13}$$

and at the end of k-th period, with a method of deduction,

$$V_k = \frac{\alpha f}{s}(1-x)(1-y^k) \tag{14}$$

On the otherhand, in the laboratory experiment,

$$V_2' = f(y^2+y) \text{ and}$$

$$V_k' = fy(1-y^k)/(1-y). \tag{15}$$

The ratio between V_k and V_k' is,

$$r = \frac{1-x}{s}\ \frac{1-y}{y} \tag{16}$$

That is, r is independent of k. The Explorer result shows that r becomes smaller as k becomes larger. Therefore, we proved conclusively the first order kinetic model can neither describe the radiation damage of MOSFET in a single orbit, nor in an accumulation of orbits.

A similar situation has been recognized in a different electronic device. In the radiation damage and annealing of solar sells, we found a fractionation effect,[5] namely, the annealable damage is dependent on the instantaneous degree of the damage, and if radiation is interrupted with an intermittent annealing, the resultant damage is much less than the damage caused by a continuous radiation with the same flurence, over a time period including both that of radiation and of annealing. We found that the result can be explained by assuming that the activation energy of annealing increases as the degree of the damage is increased.[6] The modified kinetic equation thus becomes,

$$\frac{dn}{dt} = - \frac{n}{\tau_o} \exp(-\beta n^{1/3}) + \alpha\phi \qquad (17)$$

where τ of Eq. (4) is now replaced by $\tau_o \exp(n^{1/3})$, with τ_o the recovery time at infinitesimal damage, and β is a numerical parameter related to the radiation sensitivity of the device.

To investigate Eq. (17) analytically is not possible because of its highly non-linear nature. Therefore, numerical computation has to be applied and this problem will be presently discussed.

In Eq.(6), if t is measured in the unit of orbital period, then $a = \pi$ Denoting $t = \tau_o\mu$, and $\beta^3 n = m$, Eq. (17) is reduced to

$$\frac{dm}{d\mu} = - m\exp(-m^{1/3}) + \beta^3\tau_o\alpha A\sin^2(\pi\tau_o\mu) \tag{18}$$

that is, the kinetic equation has two independent parameters, A and $\pi\tau_o$. In addition, since we are only interested in the long term behaviour, $\pi\tau_o\mu$ will represent many orbits and the detailed behavior of each orbit is not an immediate interest. Therefore, Eq. (18) is only a one-parameter equation, namely, that of $\beta^3\tau_o\alpha A$ which will be denoted by A'. Since m is a linear function of n, m is a linear function of $V_{GT}=V$, one can directly study V as a function of B.

The method to determine B from experimental data is as follows:

(1) With the best estimation from the data, V shows a periodicity with the same period as that of the satellites, and the absolute amplitude of the periodic V, that is, from the minimum to maximum of ΔV_{GT} at each period is about 20 mv, the quantization level of analog-digital conversion.

(2) The slope of V is a function of t, i.e. the number of orbit, after a long time in orbit is almost a straight line with a slope $\simeq$ 1 mv/orbit.

The above quantitative data are for a special MOSFET designated as VGT1 by Wolfgang. Different transitors behave in a quantitatively different way. This can be accommodated by changing the values of parameter A'. Since A is the same for all transistors as they all experience same radiation environment, the cause of variation in A' among different transitors is caused by β, τ_0 or α and the result is very sensitive: a small change in A' causes a drastic difference in the behaviour of m. Fig. 2 illustrates this point. When A' = 2.5, there is a rapid increase of m in the early orbits, and then reaches a saturation. When A' value is doubled, m increases almost linearly as the number of orbits is increased.

Fig. 3 shows in detail the function m for three cases, all under the same sine square radiation orbit and a periodic fluctuation is observed in all cases. Curve (1) is for first order kinetics. As can be seen from Eq. (8), m saturates at large number of orbits, independent of the value of A'. If τ is infinitely large, that is, there is no annealing term, increases with periodic inflections, but without minima, and divergences. In the case of our proposed Eq. (18), m has initial rapid rise, but with obvious maxima and minima, eventually reaches a saturation or a continuous rise, as discussed in Fig. 2.

We will show now that Eq. (18) represents the space data well. First, we will discuss the data of the transistor VGT8. Wolfgang fit the data empirically by a straight line without physical interpretation. The curve obtained from Eq. (18) shows a better fit in the sense of smaller standard deviation. The value of ΔV_{GT} is obtained from a comparison of ΔV_{GT} and m at 140 orbits which gives $m=1.0\Delta V_{GT}$(Fig 4.)

The next data we wish to discuss is for VGT1. By fitting at the data near 140 orbits, we obtained the conversion constant from m to ΔV_{GT} for different values of A'.(See Fig. 5)

When A' changes from 0 to 2.5, a satisfactory fit is obtained when A' = 2.8. A remarkable result is an initial rapid increase of ΔV_{GT}. This effect was observed in space data and Wolfgang thought this was due to a large temperature variation. A difficulty in this interpretation is that taansistors with the same circuit configuration show a same behavior with good statistics, and is different appreciably from other transistors with different circuitry configurations. Therefore, it is not possible to explain the observed permanent effect. We have been able to show here this large shift is an inherent feature of the kinetic equation and thus, strengthened the validity of our proposed annealing model.

(2) Diffusion Theoretical Approach to Annealing Due to Acceptor Impurity Doping

I. Introduction

Radiation produces an interfacial positive charge state in metal-oxide semiconductor system and resulted in a shift of the gate threshold voltage. The positive charge can be annealed if it diffuses toward the semiconductor region where the charge is more mobile and the medium is conductive, therefore, there is no electric field effect. This process could be accelerated in principle[7] by an impurity drift field with proper sign of charges and the charge distribution. HOwever, an intentional attempt to utilize this effect has been carried out only in a limited way.[8] In particular, there is some difficulty to duplicate the specimen, and we intend to conclude that the stringency of the charge distribution may be beyond the control capability of producing the desired devices. In this respect, a theoretical analysis based on the mathematical model which reappear some physical model could be rewarding in the economy of experimental effort and the understanding of the problem.

II. Diffusion Model

In the previous report, we outlined one such approach based on diffusion equation of following type:

$$\frac{\partial n(x,t)}{\partial t} = D\,\frac{\partial^2 n}{\partial x^2} - \mu E\,\frac{\partial n}{\partial x} - \frac{n}{\tau}, \qquad (1)$$

where n is the density of radiation induced positive charge. D is the diffusion coefficient, μ is the mobility, and τ is the life time. E is the field due to a charge distribution: we have assumed an exponential concentration profile and therefore E is independent of x. We have solved Eq. (1) by standard procedure in previous report and the result gives,

c

$$n(o,t) = -\frac{2\ n_o}{\tau\ \delta^2}\ e^{\beta\delta} \sum_{m=-\infty}^{\infty} \theta_m^2 \quad \delta^2 \quad (\beta+k)\ e^{-\eta_m +} \{[(\beta+k) \quad + 1].$$

$$(\beta+k) \quad \delta + \theta_m^2 \}\cos\theta_m \tag{2}$$

where k is the surface recombination constant,

$\beta = \frac{E\ell}{kT}$ with ℓ the diffusion length, and $\delta = d/\ell$, d is the thickness of the interface region. The charge density at the termination of radiation is n_o, that is, we treat the radiation and recovery as separate steps. Two most important quantities are, θ_m and η_m : θ_m are the roots of the equation,

$$\theta_m + \delta(\beta+k) \qquad \theta_m = 0. \tag{3}$$

From the nature of trigonometrical function, m are integers extending from $-\infty$ to $+\infty$.

$$\tau\eta_m = 1 + \beta^2 + \theta_m^2/\delta\ . \tag{4}$$

From Eq. (4), if δ is sufficiently small, the exponential series converges rapidly when t is large. When this very small, the summation becomes very cumbersome. Previously, we solved small t case by a different series expansion which involves successive derivatives of transcendental functions. This turns out to be quite impractical for computer calculation and this problem is yet to be solved.

Now Eq. (2) is solved for a "pulsed" sources. In the present configuration, the defects are annealed with an accumulative effect and therefore, from Eq. (2),

$$n(t) = n_o - \int_o^t n(o,t')\, dt'$$

$$= n_o - \frac{2n_o}{\tau} e^{-\beta\delta} \sum_{m=-\infty}^{\infty} \theta_m^2 (\beta+k)(1-e^{-\eta_m t})/\{[(\beta+k)\delta+1].$$

$$(\beta+k)\,\delta + \theta_m^2\}\, \eta_m \cos\theta_m$$

Numerical calculations have been made on different set of values of β, k and τ with the time in the unit of τ.. Fig. 6 shows one example where the parameters are,

$$\beta = \frac{\varepsilon\,\ell}{2kT} = \frac{V}{\delta kT}$$

$$= 0.193 \text{ at } 300^o\text{k and } V = 10 \text{ mv},$$

$$k = .1, \quad \delta = 2.$$

This is for Curve I in the figure. Curve II is for same values of k and δ, but $\beta = 0$. The total annealed defect in the presence of the drift field (curve I) is obviously higher then the case of no drift field.

The above results are obtained with one assumption, namely, the concentration of defect is very large such that the defects removed by annealing is negligiable. The case for finite concentration is not carried out in the present work. The above results also assume that the diffusion of defects through the interface is an uncorrelated diffusion. The formulation for correlated diffusion can be found in the work of Waite[9)] However, in this approach, one can only introduce impurities with uniform distribution, that is, there is no field effect. Similar results apply to the model of Simons and Hughes[10] where the spatial dependence such as barrier effect are not possible to be introduced and one wonders under such a restriction, whether the physical model has suffered.

SUMMARY

This report covers two subjects and the principal results are:

1) For the analysis of radiation damage data of MOSFETS, we proposed a kinetic equation for simultaneous radiation damage and annealing. The equation fits well the data from Explorer 34 reported by Wolfgang. Therefore, besides providing physical insight to the behaviour of MOSFETS in radiation environment, the results provide a theoretical basis to predict the long term behaviour of MOSFET devices in space satellites.

2) For a modified MOS structure by introducing boron layer, we formulated a diffusion model which supports the idea that a concentration gradiant field can be introduced which would accelerate the annealing of radiation damage.

I would like to acknowledge the kind cooperation of V. Danchenko and J. Wolfgang in discussing their interesting experimental results and I sincerely hope that this technical cooperation would continue beyond the termination of the contractual relation. Numerical calculations on computers were made by E. Richards and I am indebted to him for the results.

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LIST OF FIGURES

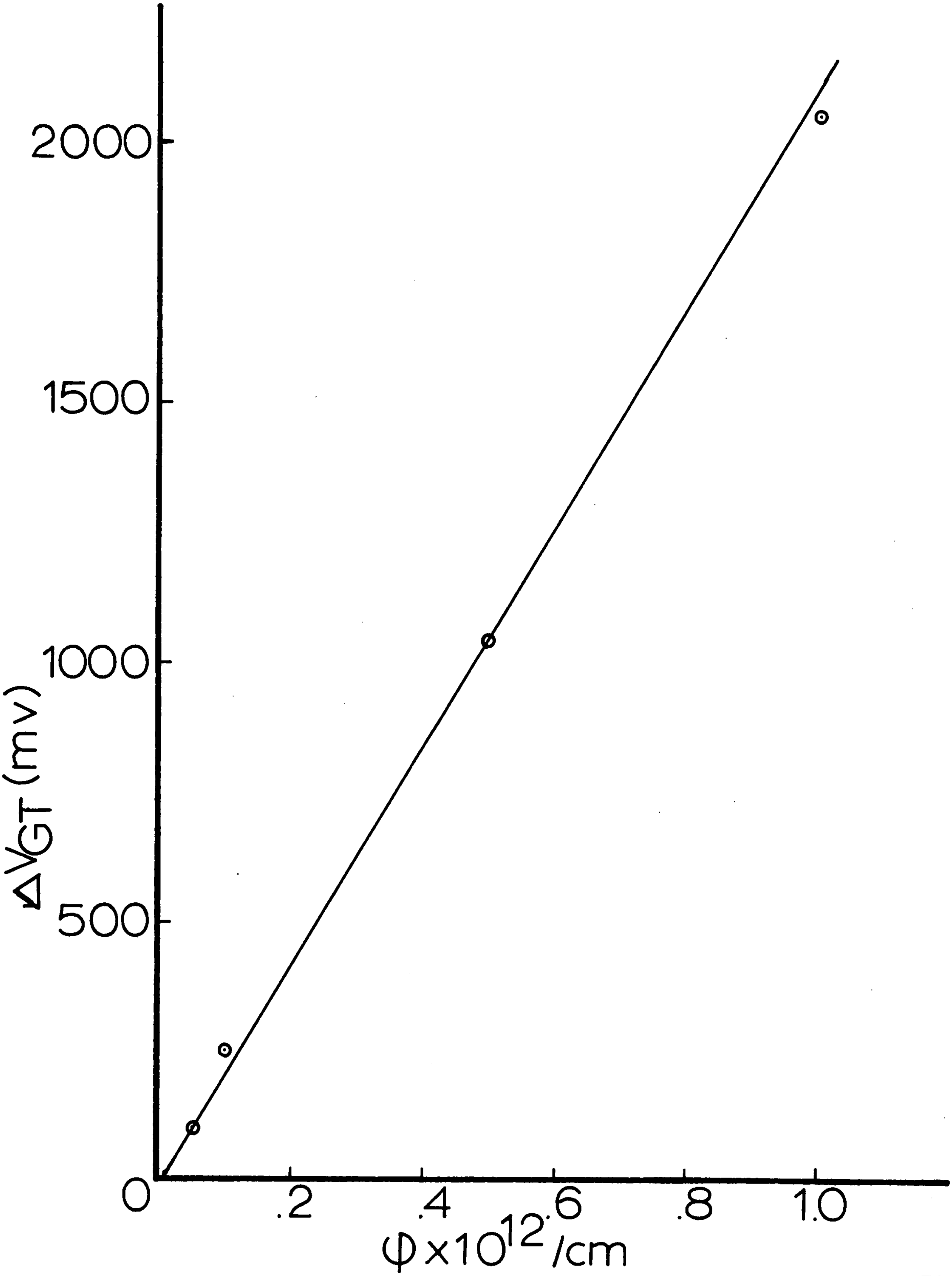


Fig. 1

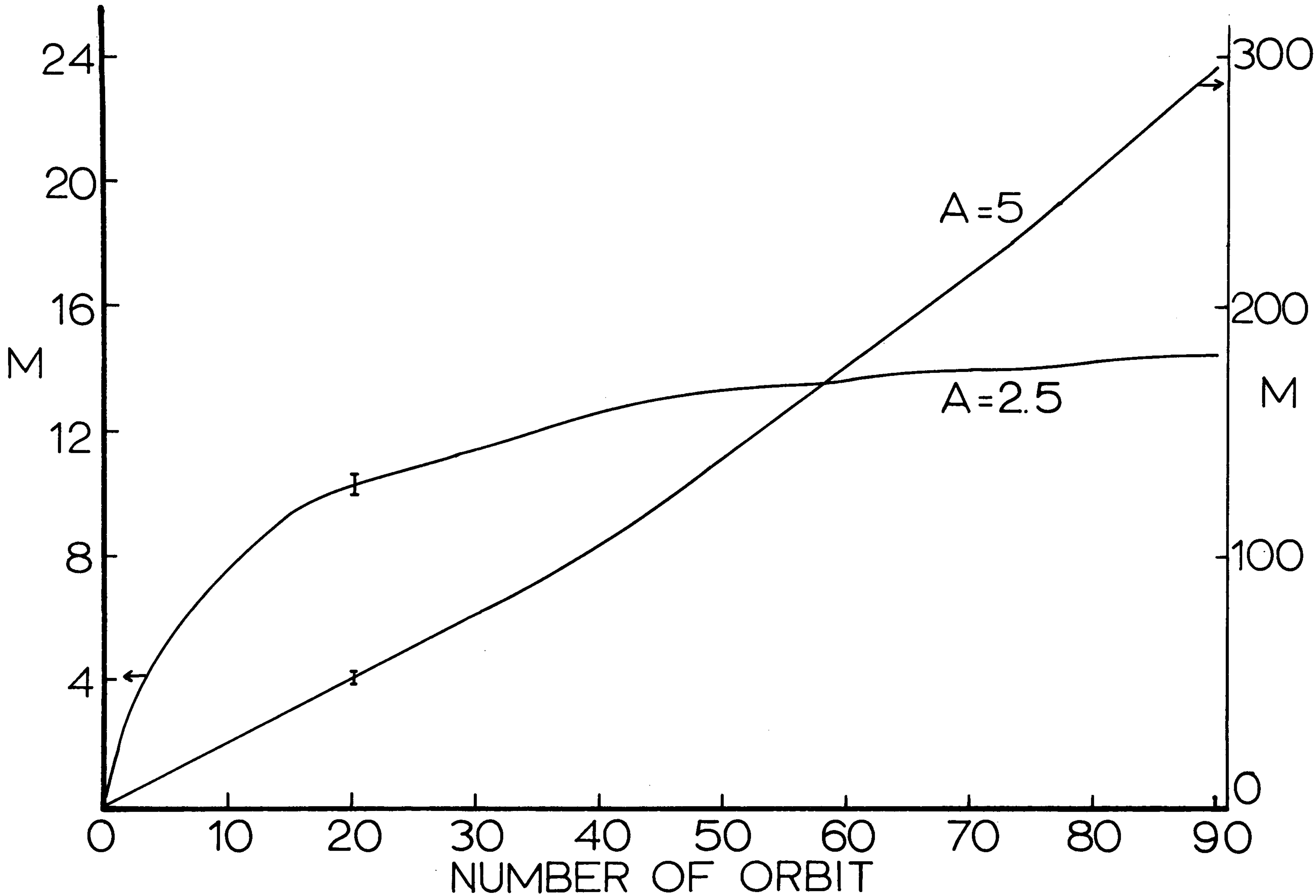

24
20
16
12
8
4
M
300
200
100
0
M
A=5
A=2.5
0
10
20
30
40
50
60
70
80
90
NUMBER OF ORBIT

Fig. 2

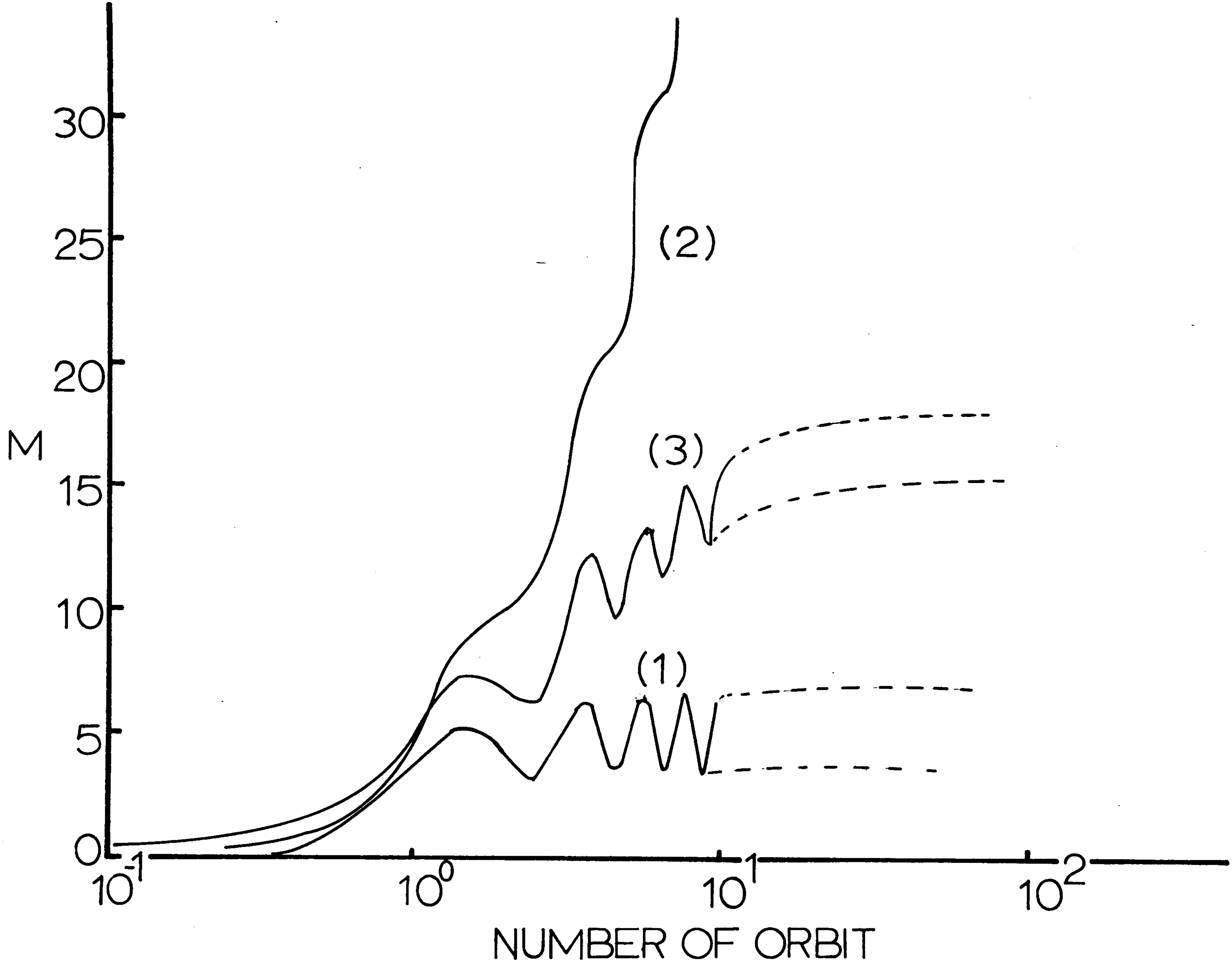
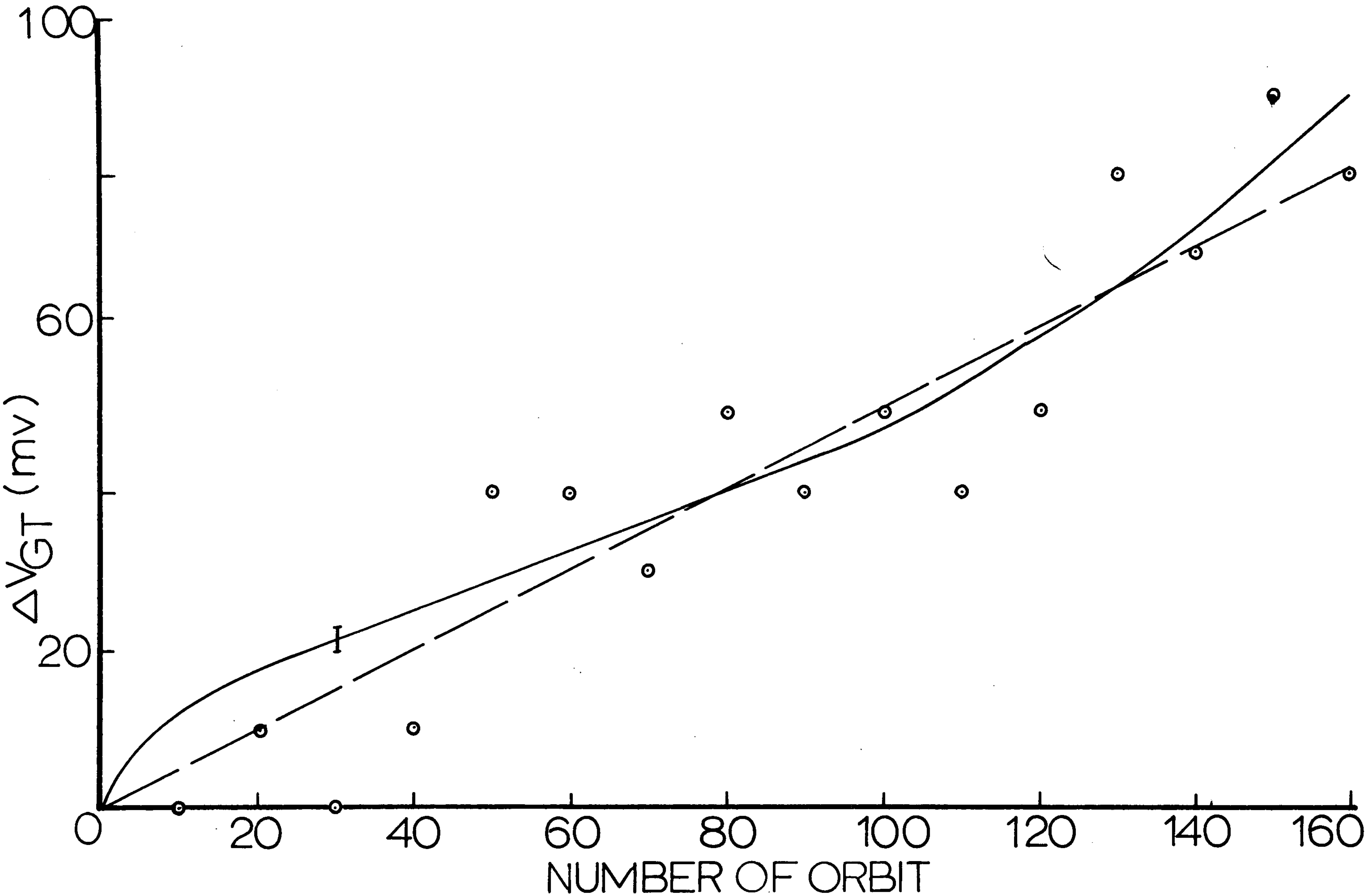
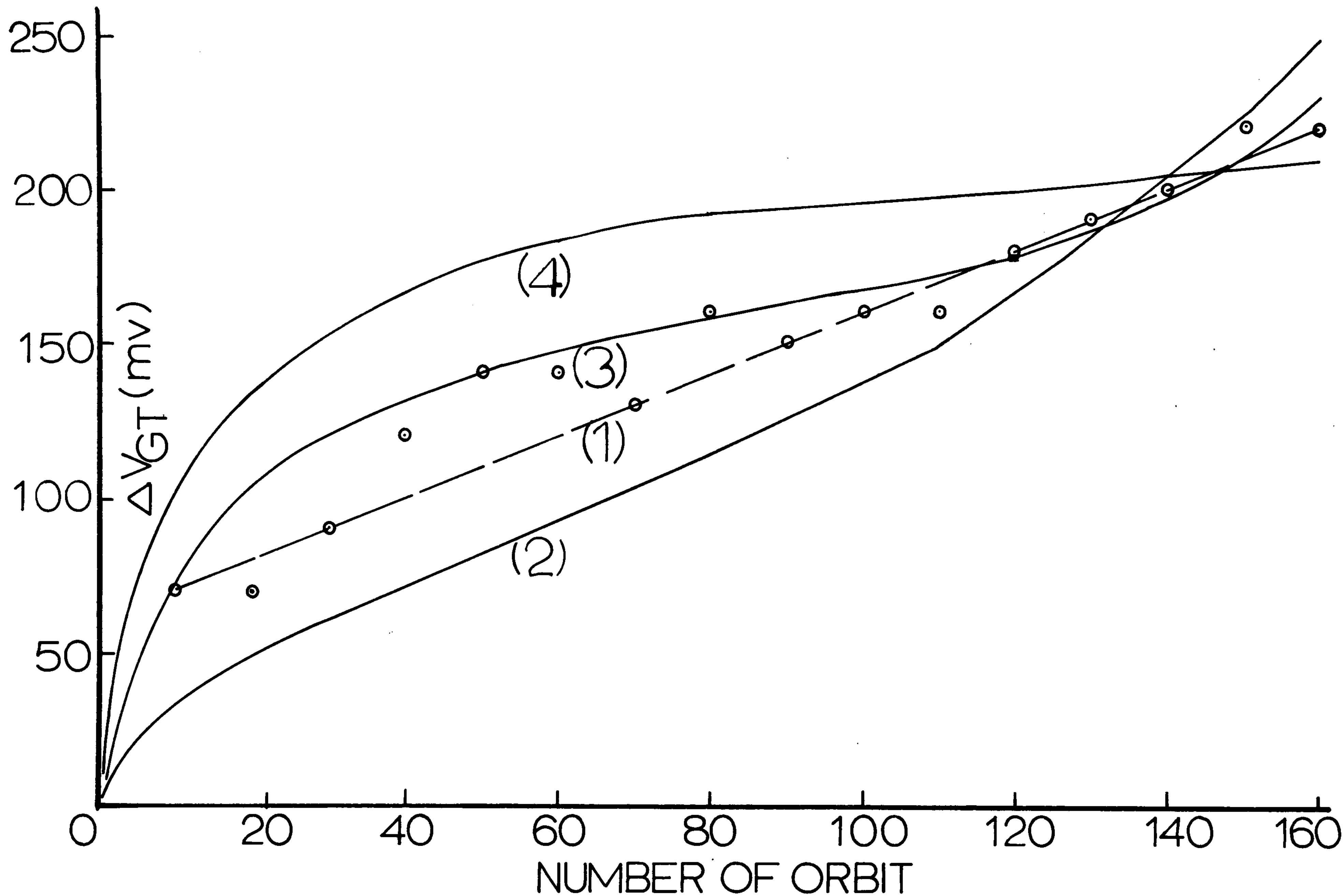


Fig. 3



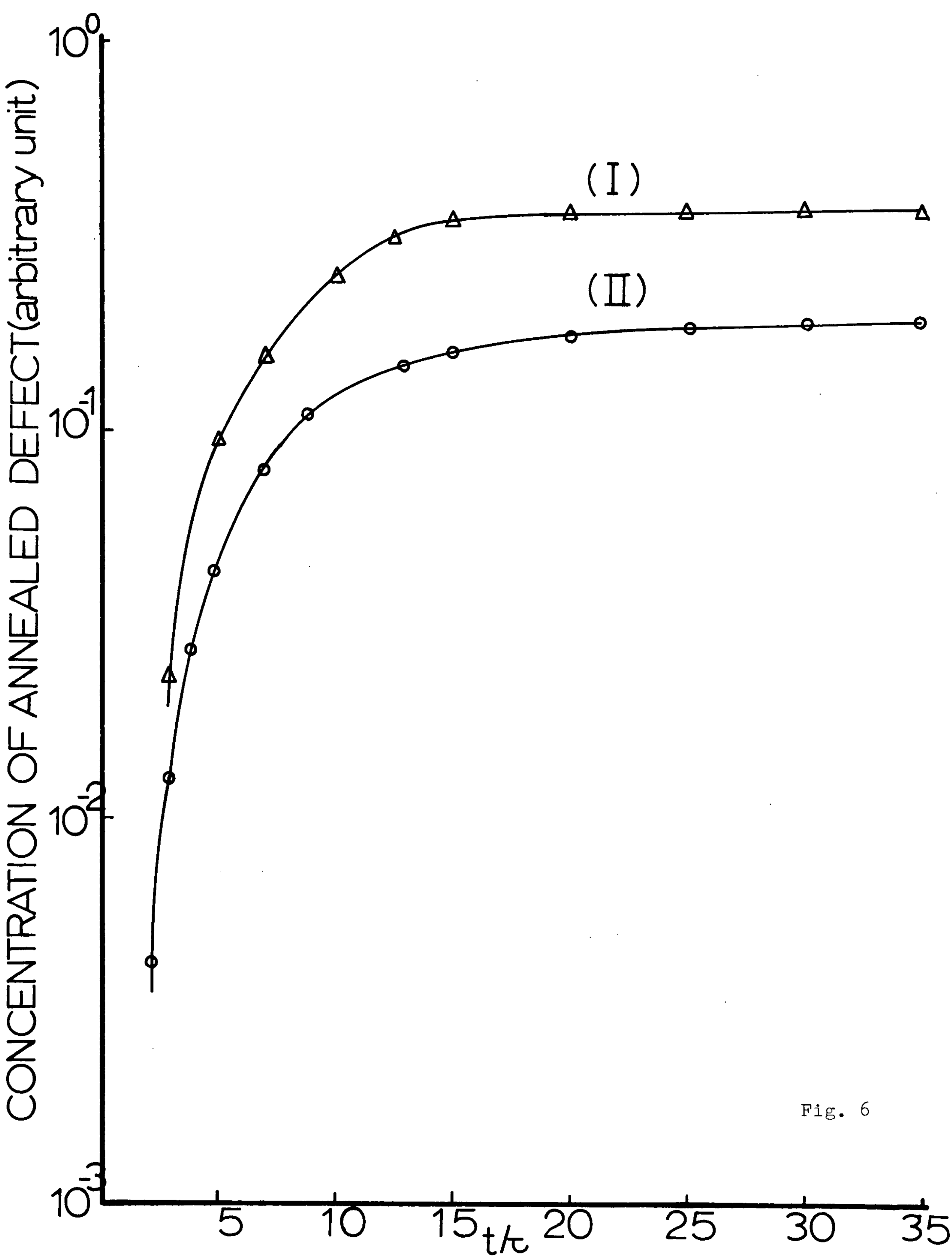
100
60
20
0
ΔV_{GT} (mv)
20
40
60
80
100
120
140
160
NUMBER OF ORBIT

Fig. 4



250
200
150
100
50
0
20
40
60
80
100
120
140
160
ΔV_{GT} (mv)
NUMBER OF ORBIT
(1)
(2)
(3)
(4)

Fig. 5



CONCENTRATION OF ANNEALED DEFECT(arbitrary unit)
10^0
10^{-1}
10^{-2}
10^{-3}
(I)
(II)
5
10
15
t/τ
20
25
30
35

Fig. 6