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Heavy Ion Induced Soft Breakdown of Thin Gate Oxides

J.F. Conley, Jr.,[1] J.S. Suehle,[2] A.H. Johnston,[1] B. Wang,[3] T. Miyahara,[1] E.M. Vogel[2]

[1]NASA Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA 91109, john.f.conley@jpl.nasa.gov
[2]National Institute of Standards and Technology, Bldg. 225, B360, Gaithersburg, MD 20899
[3]Center for Reliability Engineering, University of Maryland, College Park, MD, 20742

Heavy ion induced soft and hard breakdown are investigated in thin gate oxides as a function of LET, fluence, and voltage applied during irradiation. It is found that post-irradiation oxide conduction is well described by the Suñé quantum point contact model.

I. Introduction

Future JPL planned missions to the outer planets will require electronics with ultra high levels of radiation tolerance (>1Mrad). Although radiation produces only a modest shift in the threshold voltage of the thin gate oxides used in advanced MOS technology, these thin oxides are still susceptible to radiation effects. In the last few years, pioneering work has uncovered a variety of new radiation-induced effects in thin gate oxides [1-10], including radiation induced leakage current (RILC) in gamma and electron irradiated oxides [1-5] and single event gate rupture (SEGR) [6-8] and radiation induced soft breakdown (RSB) [7-10] in oxides exposed to high LET heavy ion irradiation. Despite this work, the effects of radiation on the reliability of ultrathin oxides (<4 nm) have not been extensively characterized. In this work, we report on the effects of heavy ion induced soft breakdown of 3.0 and 3.2 nm thin oxide films as a function of LET, fluence, and the voltage applied during irradiation. Post irradiation oxide conduction is modeled with the Suñé quantum point contact model [11].

II. Experimental Details

Two sets of oxide test capacitors were used in this study. P-well test capacitors supplied by a commercial facility had an oxide thickness of 3.2 nm, a poly-Si gate thickness of approximately 400 nm, and an area of 10^{-3} cm^2. P-substrate research-grade capacitors supplied by a university had an oxide thickness of 3.0 nm, a poly thickness of 400nm, and areas of 10^{-4} cm^2 and 4×10^{-4} cm^2. Oxide thickness was determined by high frequency capacitance vs. voltage curves with quantum simulation of substrate quantization and poly depletion effects included. The intrinsic breakdown strength of both the 3.2 and 3.0 nm oxides was ≥ 17 MV/cm, determined by a standard voltage ramp test.

Heavy ion testing was conducted at the Brookhaven National Laboratories Tandem Van de Graff accelerator using 343 MeV ^{197}Au, 343 MeV ^{127}I, and 279 MeV ^{81}Br (respective LETs = 81.9, 59.9, and 37.5 MeV-cm^2/mg) and at the Texas A&M University Cyclotron using 2955 MeV ^{197}Au, 737 MeV ^{129}Xe, and 2861 MeV ^{129}Xe (respective LETs ≅ 80, 60, and 40 MeV-cm^2/mg). Exposures were conducted at normal incidence with capacitor gates either tied to ground or biased in accumulation.

A series of irradiations was performed sequentially on each sample. For each irradiation step, V_{app}, the gate voltage applied during irradiation, is held constant while the capacitor is exposed to a set fluence of ions. Multiple devices were irradiated at a time. I_g-V_g measurements were taken immediately following each irradiation step. An HP 4156 Semiconductor Parameter Analyzer enabled in-situ gate leakage (I_g) measurements to levels of less than 10 pA. Compliance was set to 10 mA. In some cases, another I_g-V_g curve was taken several minutes later in order to avoid a transient decrease in the post-irradiation excess leakage [9]. After several irradiation steps, the transient effect appears to dissipate and thereafter, only one trace per step is taken.

III. Results

Fig.1 shows a typical example of I_g-V_g curves as a function of V_{app}. In Fig. 1, 3.2 nm thick, 10^{-3} cm^2 capacitors were exposed to ^{197}Au (LET=80) with a fluence of approximately 10^6 ions/cm^2/step (~1000 "hits"/step), at a typical flux of roughly 1.9×10^4/cm^2/sec (+/- 15%).

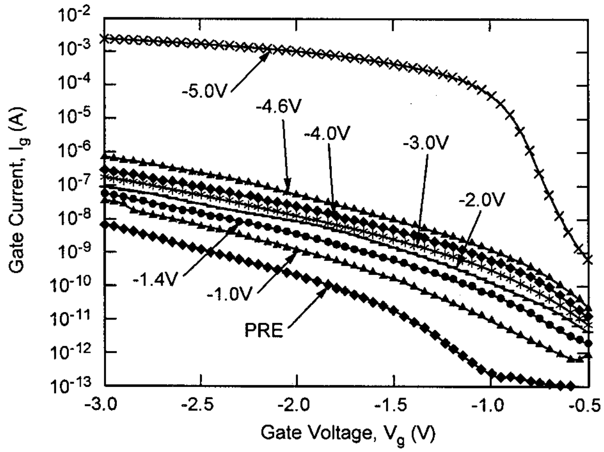

Fig. 1: I_g vs. V_g curves as a function of V_{app} for a 3.2 nm, 10^{-3} cm^2 capacitor exposed to Au(LET=80).

Fig. 2 shows oxide leakage current density, J_g (A/cm^2), as a function of V_{app} for 3.0 nm capacitors exposed to LET ≅ 82 (Au), 60 (I), and 37.5 (Br) MeV-cm^2/mg. (Note that different V_{app} steps were used for each LET.) Oxides were irradiated for 35-140 sec at a typical flux of roughly $7x10^4/cm^2/sec$ (+/- 50%) to a fluence of approximately 10^6 ions/cm^2/step. Devices at each LET were irradiated together. J_g has been extracted at V_g = -3.0V in order to quantify the amount of leakage or degree of soft breakdown while avoiding the effects of RILC and stress induced leakage currents (SILC) at the lower fields and still remaining well below the intrinsic breakdown field. Pre stress leakage current density in all cases was approximately 10^{-7} A/cm^2. Results from capacitors with areas of 10^{-4} and $4x10^{-4}$ cm^2 are plotted together. The capacitors received approximately 500 and 2000 "hits"/irradiation step, respectively. It is found that radiation induced leakage is proportional to capacitor area and that leakage density is the same for both areas [10].

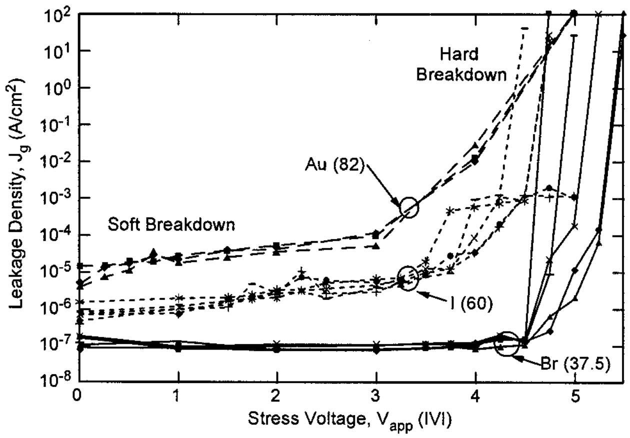

Fig. 2: Plot of J_g (extracted at V_g=3.0V) vs. V_{app} for 3.0 nm, 10^{-4} and $4x10^{-4}$ cm^2 capacitors exposed to Au (LET=82), I (LET=60), and Br (LET=37.5).

From Figs. 1 and 2, it is clear that the post radiation oxide conduction in these thin oxides is a function of both LET and bias (as reported in [9,10] and in thicker oxides by [6-8]). For the case of Br, the oxides go straight to hard breakdown (HBD), as observed in electrical tests. For both Au and I, however, the oxides first exhibit soft breakdown (SBD) at zero voltage which gradually increases at low voltage [8-10] before finally succumbing to hard breakdown at higher voltage. SBD is indicated by the >10x increase in I_g, increased noise, and the exponential dependence of leakage on V_g, (at the higher voltages, I_g-V_g curves appear as nearly straight lines on the log-linear scale). Note also that subsequent traces are roughly parallel. In the reliability literature, the first SBD is considered destructive [12,13].

Qualitatively, it appears as though the field required for HBD decreases with LET, confirming earlier work in thicker oxides [6-8].

Fig. 3 shows heavy ion (^{127}I, LET = 60) induced oxide leakage current density (A/cm^2) as a function of fluence and V_{app}. In this figure, J_g is an average of at least two capacitors for each V_{app}. Again, results from 3.0 nm oxides with area = 10^{-4} and $4x10^{-4}$ cm^2 are used and J_g is extracted at V_g = -3.0V. V_{app} is held at a constant voltage during each subsequent radiation step until a fluence of $2x10^8$ is achieved. Flux varied from $3x10^3$ to $2.4x10^5$ ions/cm^2/sec; exposure time varied from 34 to 425 sec.

From Fig. 3, it is seen that 1) leakage is a strong function of fluence over several decades, 2) increased leakage is observed *even at the lowest fluence* (a fluence of $2x10^5/cm^2$ corresponding to roughly 15 and 60 "hits" for the 10^{-4} and $4x10^{-4}$ cm^2 capacitors), 3) leakage is also a function of V_{app}, though it has a weaker dependence than on fluence, 4) increased leakage is observed even at zero applied voltage. A similar dependence of leakage on fluence was reported in thicker oxides by Sexton *et al.* [6] and in thin oxides at higher fluence by the Ceshia *et al.* [9,10].

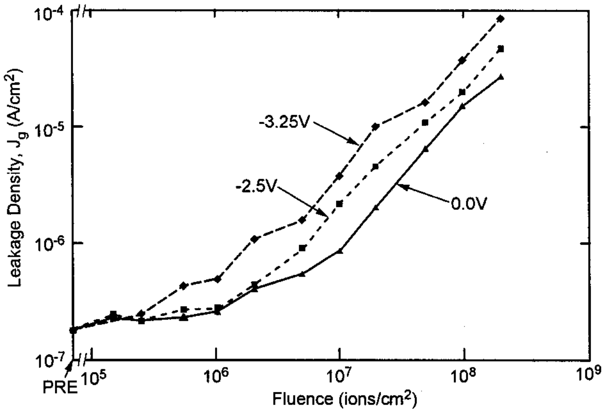

Fig. 3: Plot of J_g (extracted at V_g=3.0V) vs. fluence for 3.0 nm, 10^{-4} and $4x10^{-4}$ cm^2 capacitors exposed to I (LET=60) with V_{app} = -3.25, -2.5, or 0.0 V.

Post electrical stress oxide conduction has recently been modeled by Suñé and Miranda [11] as a localized breakdown that behaves as a quantum point contact. The current-voltage relationship can be expressed as:

$$I = A\exp^{-\alpha\phi}\exp^{BV}, \qquad (1)$$

where $A = 4e/\alpha h$, $B = \alpha e/2$, e is the electronic charge, h is Plank's constant, and V is the voltage drop across the oxide. The two parameters associated with this model are ϕ, the barrier height of the quantum saddle point contact in units of eV, and α, which has units of 1/eV and is correlated to the shape or thickness of the contact. The amount of current that tunnels through an energy barrier is proportional to the inverse of the area of the barrier. The QPC barrier area can be approximated by its thickness times its height. More current flows for thinner (smaller α) and lower (smaller ϕ) barriers.

Fig. 4 shows a typical example of post irradiation I_g-V_g curves as a function of fluence for a constant bias during the irradiation. In this case, the 3.0 nm, 10^{-4} cm^2 capacitors were exposed to ^{127}I (LET = 60) ions with V_{app} = -2.5 V. Simulations using fits to Eqn. 1 are shown by the dashed lines. Note that the fits are quite good, especially at larger voltages.

Fig. 5 shows the extracted ϕ and α as a function of fluence for the same capacitors exposed at V_{app} = -3.25 V. α is related to the slope and ϕ is related to α and the y-intercept. Note that ϕ is relatively constant as a function of fluence until about $5x10^7$ ions/cm^2 where it drops below 3.2 eV. According to [11], the drop of ϕ below 3.2 eV suggests the onset of hard breakdown. Note that α decreases as a function of fluence. A decrease in α can be modeled as the formation of multiple quantum point contacts in parallel, each with the same ϕ. It is reasonable and might even be intuitively expected that for the same LET and voltage, the effect of additional fluence is to create additional similar QPCs. This situation might be imagined as the heavy ion exposure turning the oxide into a "swiss cheese", with each (or nearly every) ion creating its own "tube" or QPC percolation filament. A summation of these paths gives the total leakage. This result is consistent with earlier reports [8-10].

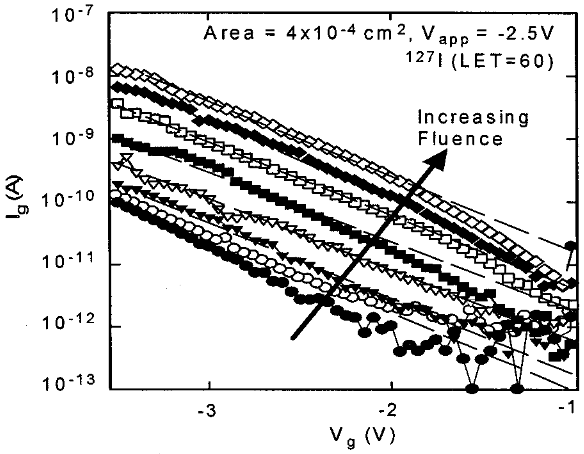

Fig. 4: I_g vs. V_g curves as a function of fluence for a 3.0 nm, 10^{-4} cm^2 capacitor exposed to I (LET=60) with V_{app} = -3.25 V. Dashed lines represent fit to theory.

Fig. 6 shows the extracted values of ϕ and α as function of V_{app}, the voltage applied during irradiation. Note again that ϕ is relatively constant with voltage and that α decreases with voltage. An interpretation of the QPC model suggests that the larger voltages induce QPCs with thinner barriers (smaller α), thus allowing more current to flow. Once again, the drop of ϕ below 3.2 eV is accompanied by a large increase in I_g or hard breakdown.

Finally, Fig. 7 shows that the ϕ is sensitive to LET. This result suggests that larger LET ions produce a more broadly damaged region, perhaps with a wider path with a quantum mechanically lower barrier height (lower ϕ) that allows more current to flow.

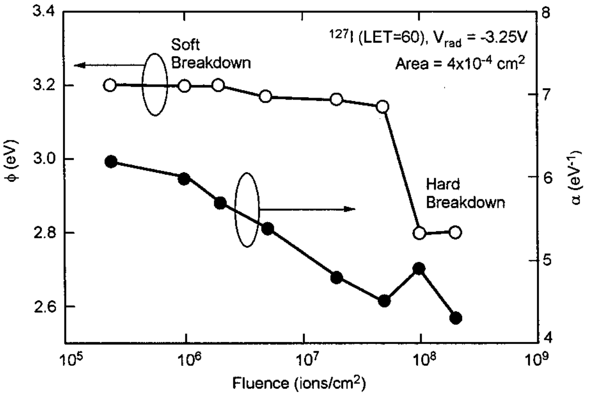

Fig. 5: Extracted ϕ (open) and α (solid) vs. fluence for a 3.0 nm, $4x10^{-4}$ cm^2 capacitor exposed to I (LET=60) with V_{app} = -3.25 V.

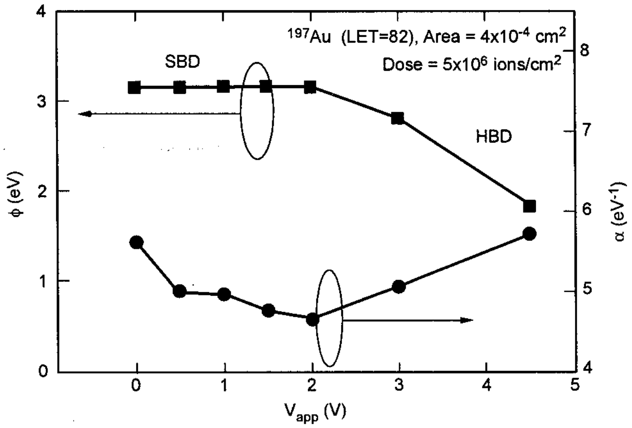

Fig. 6: Extracted ϕ (squares) and α (circles) vs. V_{app} for a 3.0 nm, $4x10^{-4}$ cm^2 capacitor exposed to $\sim 5x10^6$ Au (LET=82) ions/cm^2.

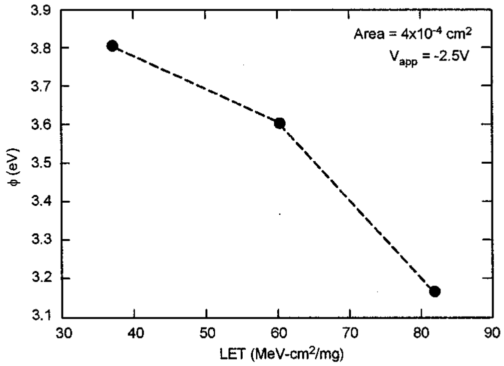

Fig. 7: Extracted ϕ vs. LET for a 3.0 nm, $4x10^{-4}$ cm^2 capacitor exposed to $\sim 5x10^6$ ions/cm^2. at V_{app} = -2.5 V.

IV. Discussion

From Figs. 1-3, it is found that heavy ion induced leakage depends on LET, fluence, and V_{app}, in decreasing importance. In Figs. 4-7, the QPC model is used to model heavy ion induced conduction in thin SiO_2. It is found that α depends inversely on fluence and V_{app} and that ϕ depends inversely on LET. Our interpretation is that the size of the QPC path is dependent on LET and voltage while the number of paths depends on the fluence. A drop of ϕ below 3.2 eV indicates transition from SBD to HBD [11]. As LET increases this transition occurs at lower voltage.

There is controversy in the literature [1,6-9] as to whether heavy ion irradiation will be a threat to gate oxides in scaled devices. Although the results reported here show that the voltage required for HBD/SEGR is reduced as LET and fluence are increased (confirming earlier reports in thicker oxides [6-8]), the field required for the onset of SEGR are outside the realm of today's normal device operation. Future scaling, however, may bring operating voltages into this regime. SEGR may be relevant for applications such as FPGAs which rely on thin dielectrics for programming at high fields.

What may be more of a concern is RSB. In previous studies of SEGR, RSB was noted but was not studied in detail [6-8]. RSB in thin oxides at high fluence has been studied by Ceshia *et al.* [9,10]. Sexton *et al.* [8] referred to RSB as "precursor ion damage" and concluded that, due to the high fluence required, it was not an important failure mechanism. However, in the reliability literature the first SBD is considered destructive to the oxide [12,13]. Whether it is actually harmful to the device or circuit will likely depend on the application. There are several situations in which even small amounts of leakage may have an impact on device or circuit operation. It is likely that analog, low power, and memory applications may be susceptible, but it is not clear at what point this would be come a serious issue for digital CMOS. However, the observation here of RSB at low fluence ($2x10^5/cm^2$) and at zero applied fields is a cause for concern as at high enough LET, even "powered down" parts may be susceptible. In addition, because RSB is proportional to area, total gate areas in future scaled devices with 100's of VLSI devices may increase system susceptibility to RSB.

V. Conclusions

In the reliability community, SBD is considered the first permanent change in oxide structure [12,13] and it is defined as destructive because it is not clear how the oxide will behave after this first SBD event. Ten year lifetime extrapolations are based on this first SBD event. Thus, RSB in thin oxides may also more properly be considered as destructive. More work is needed to fully understand this damage mechanism and whether it poses a threat to the use of MOS devices in space.

VI. Acknowledgements

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[1]*California Institute of Technology, ~~NASA~~ Jet Propulsion Lab,*
Pasadena, CA

[2]*NIST, Gaithersburg, MD*

[3]*Center for Reliability Engineering, University of Maryland,*
College Park, MD

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Outline

1. Motivation
2. Experimental Details
3. Experimental Data:

   Post-rad I_g vs.
   - V_{app}
   - Fluence
   - LET
   - Area

4. Sune Quantum Point Contact Model
5. Analysis: Fit of Sune Model to data
6. Conclusions

Introduction

- Gate oxide thickness continues to scale down.
- Although radiation only produces modest threshold voltage shifts, thin oxides are still susceptible to a variety of radiation effects:
  - RSB and RILC: Padova Group

    RILC: Paccagnella *et al.*, NSREC '96, '97, '98, '99

    RSB: Ceshia *et al.*, IEEE RADECS '00 and NSREC '00
  - SEGR: Sexton *et al.*, NSREC '97, and NSREC '98

    Johnston *et al.*, NSREC '98
- Despite this recent work, the effects of radiation on the reliability of ultra-thin oxides has not been extensively studied.

Experimental Details

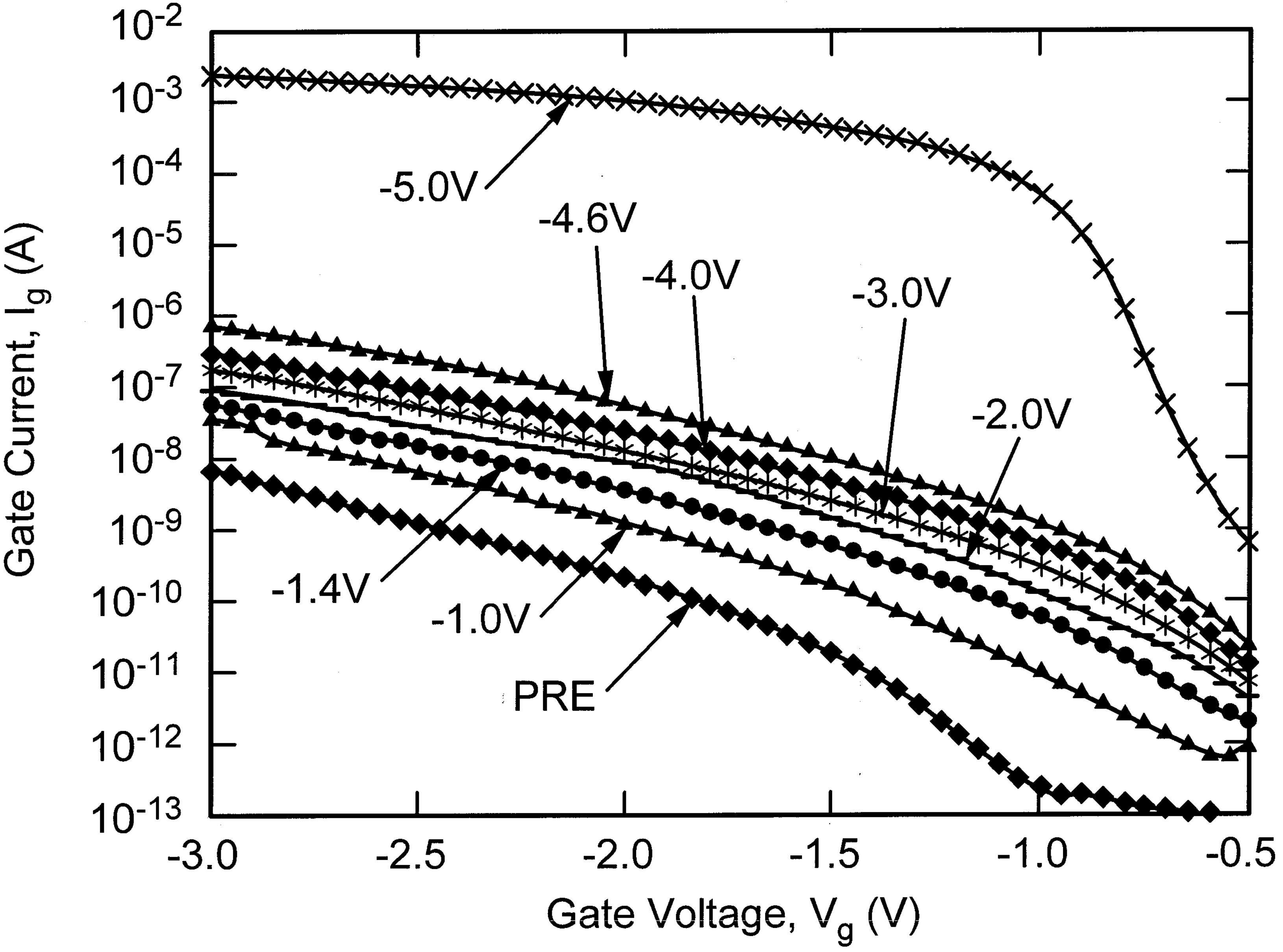
Samples: 1) 3.0 nm SiO_2 p-well caps, 10^{-4} & $4x10^{-4}cm^2$ (univ.)
2) 3.2 nm SiO_2 p-well caps, 10^{-3} cm^2 (comm.)

Heavy Ions: 1) Brookhaven Tandem Van de Graff
- 343 MeV Au, 343 MeV I, and 279 MeV Br
(LET = 81.9, 59.9, and 37.5 MeV-cm^2/mg))

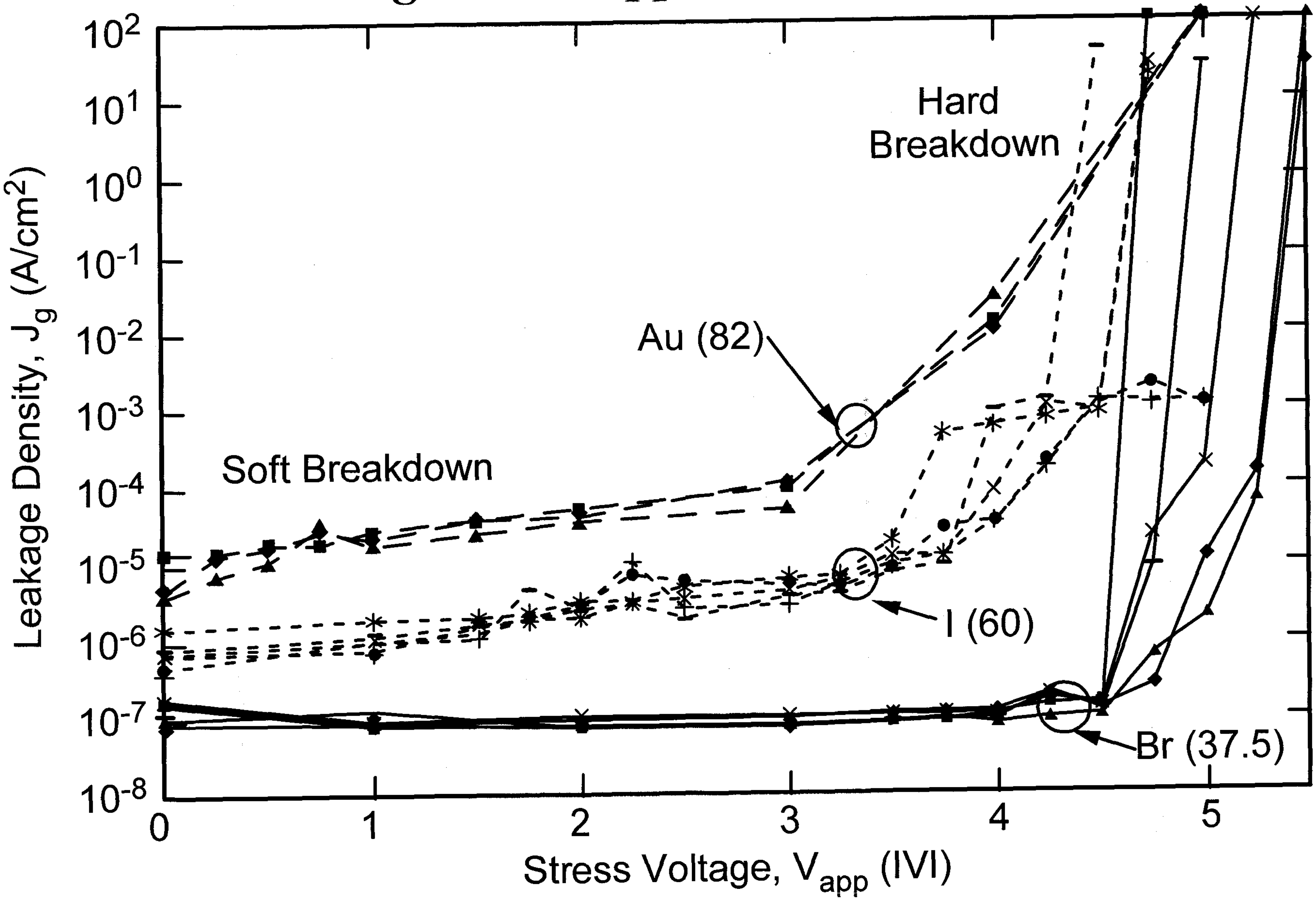
2) Texas A&M Cyclotron
-2955 MeV Au, 737 MeV Xe, & 2861MeV Xe
(LET $\cong$ 80, 60, and 40 MeV-cm^2/mg))

Procedure:
1) Irradiate under constant gate bias
(~60 sec, ~10^6 ions/cm^2/step)
2) Measure gate leakage (Agilent 4156)
3) Increase gate bias
4) Repeat

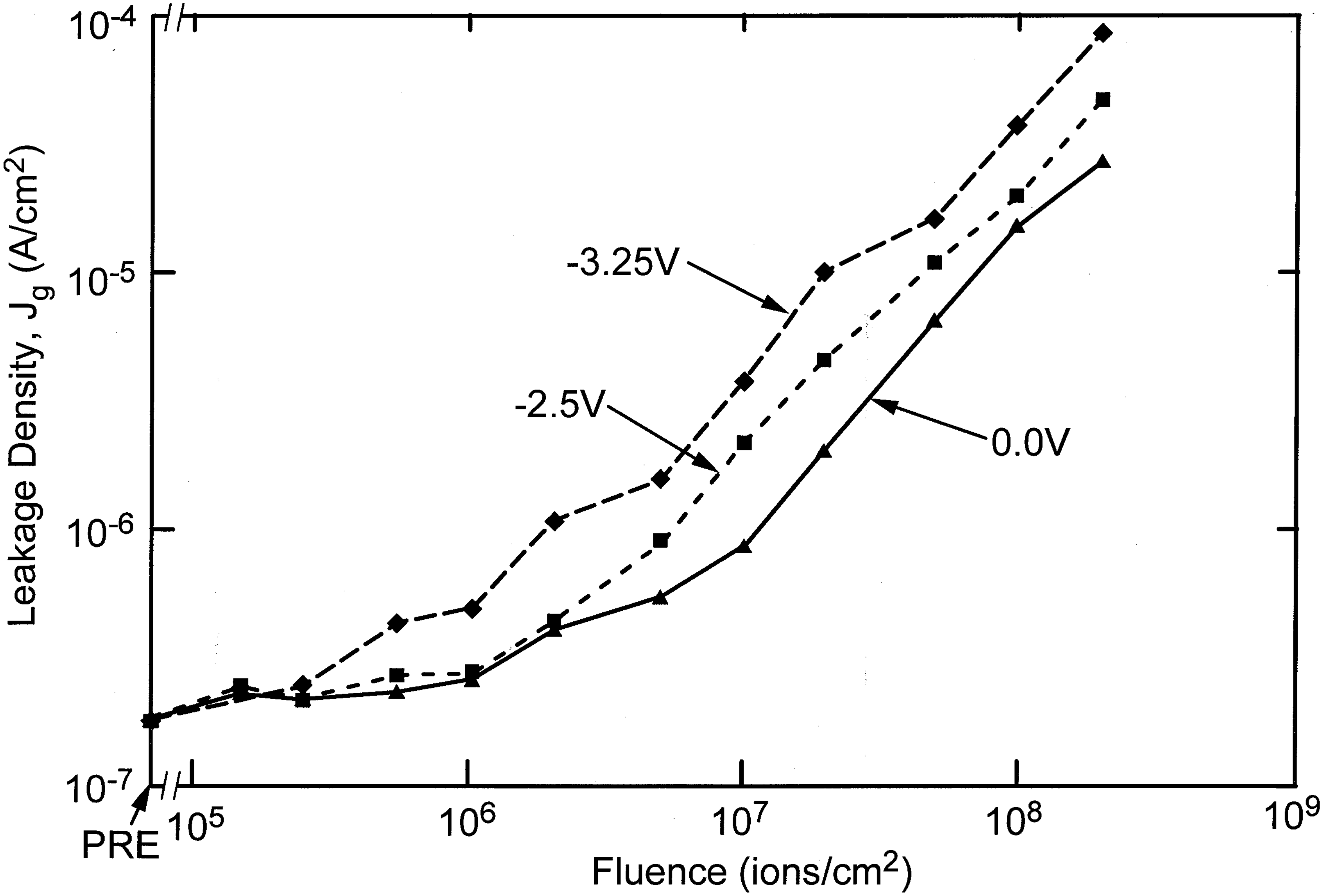
Typical I_g-V_g Curves as a Function of V_{app}



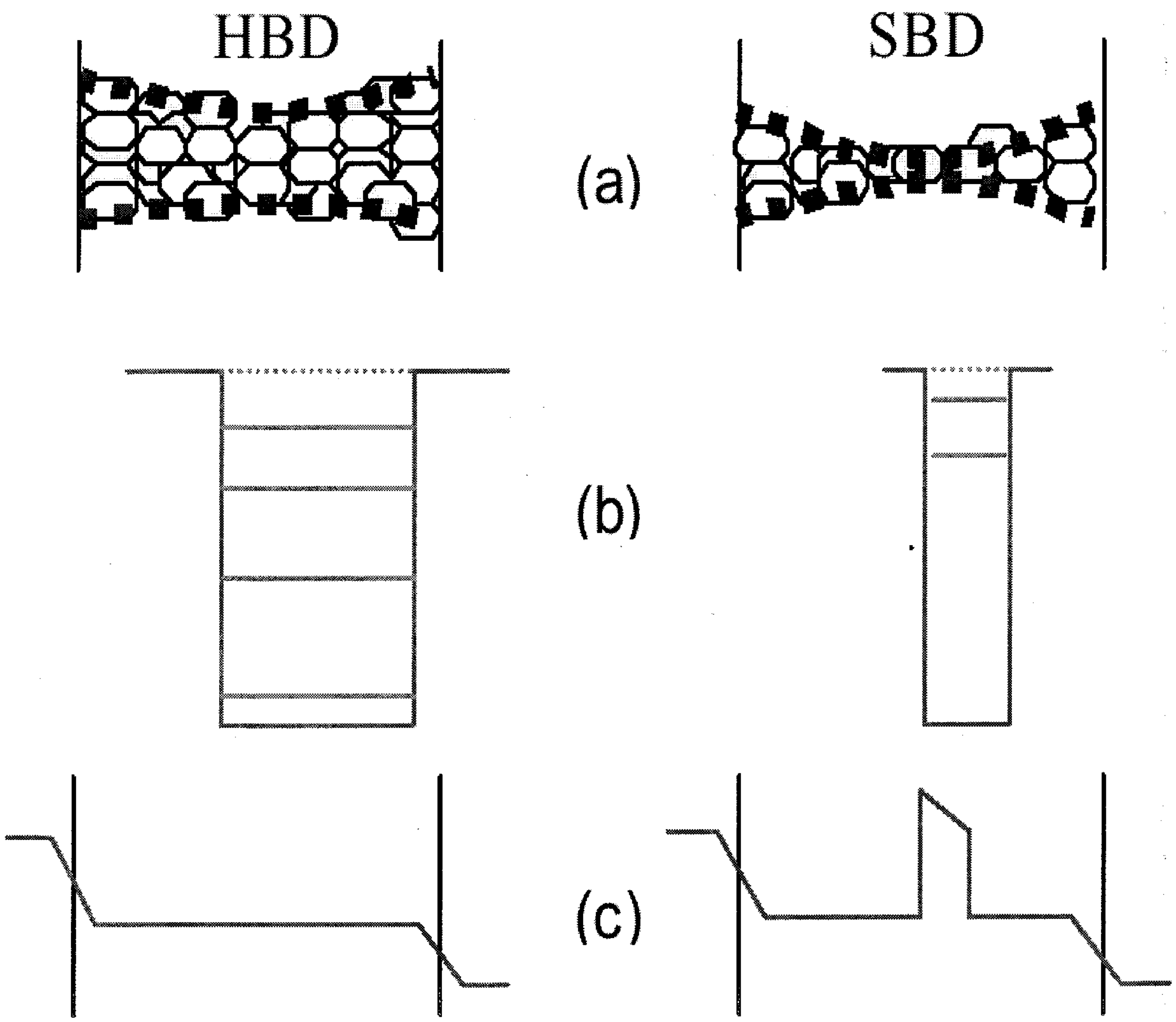
Plot of J_g vs. V_{app} for Various LET



Plot of J_g vs. Fluence for Various V_{app}



Sune Quantum Point Contact Model



$$I = A\exp^{-\alpha\phi}\exp^{BV}$$

$A = 4\alpha e/h$, $B = \alpha e/2$

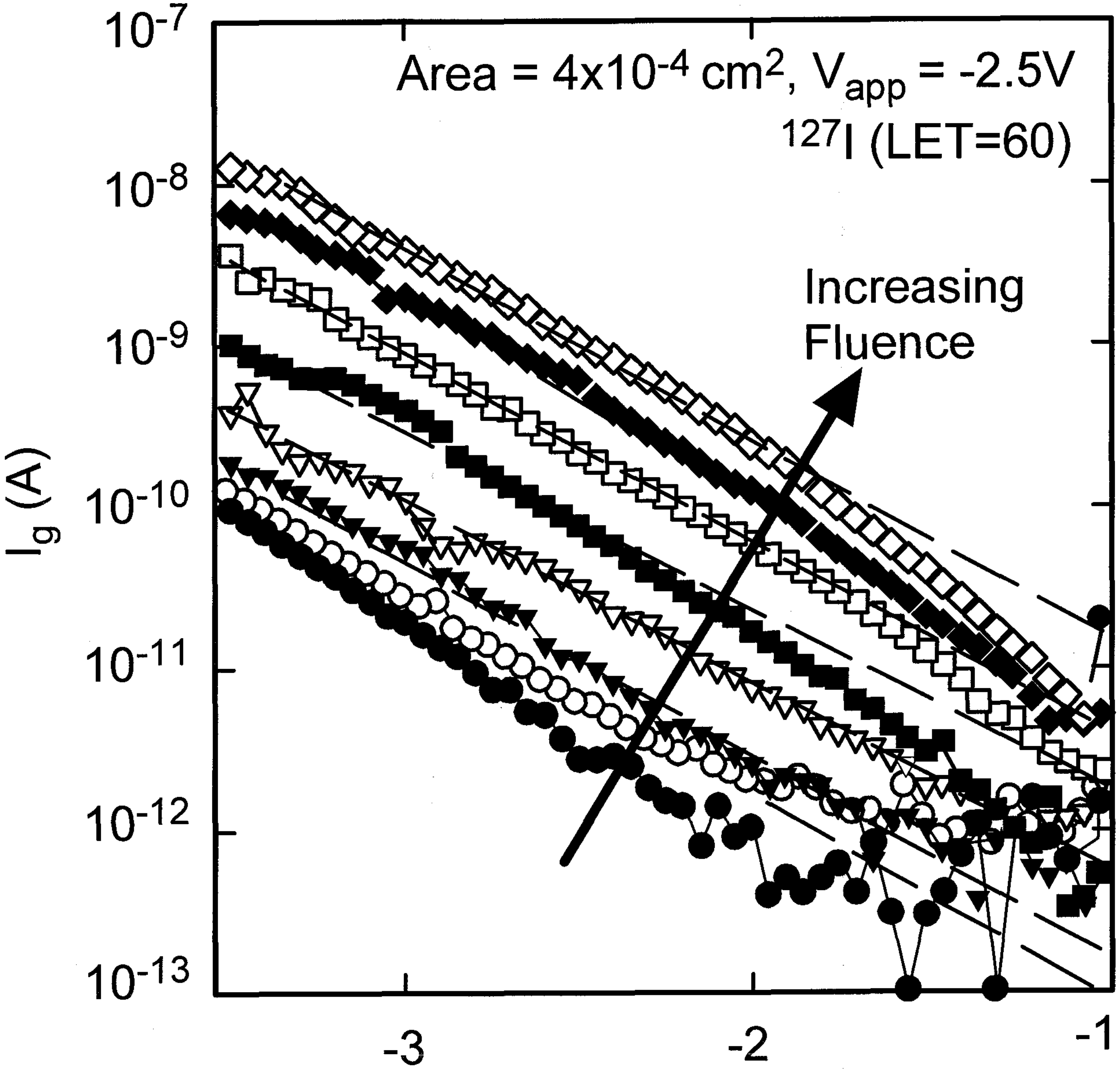
<u>Model Parameters</u>

α: $\propto$ Barrier Height (eV)

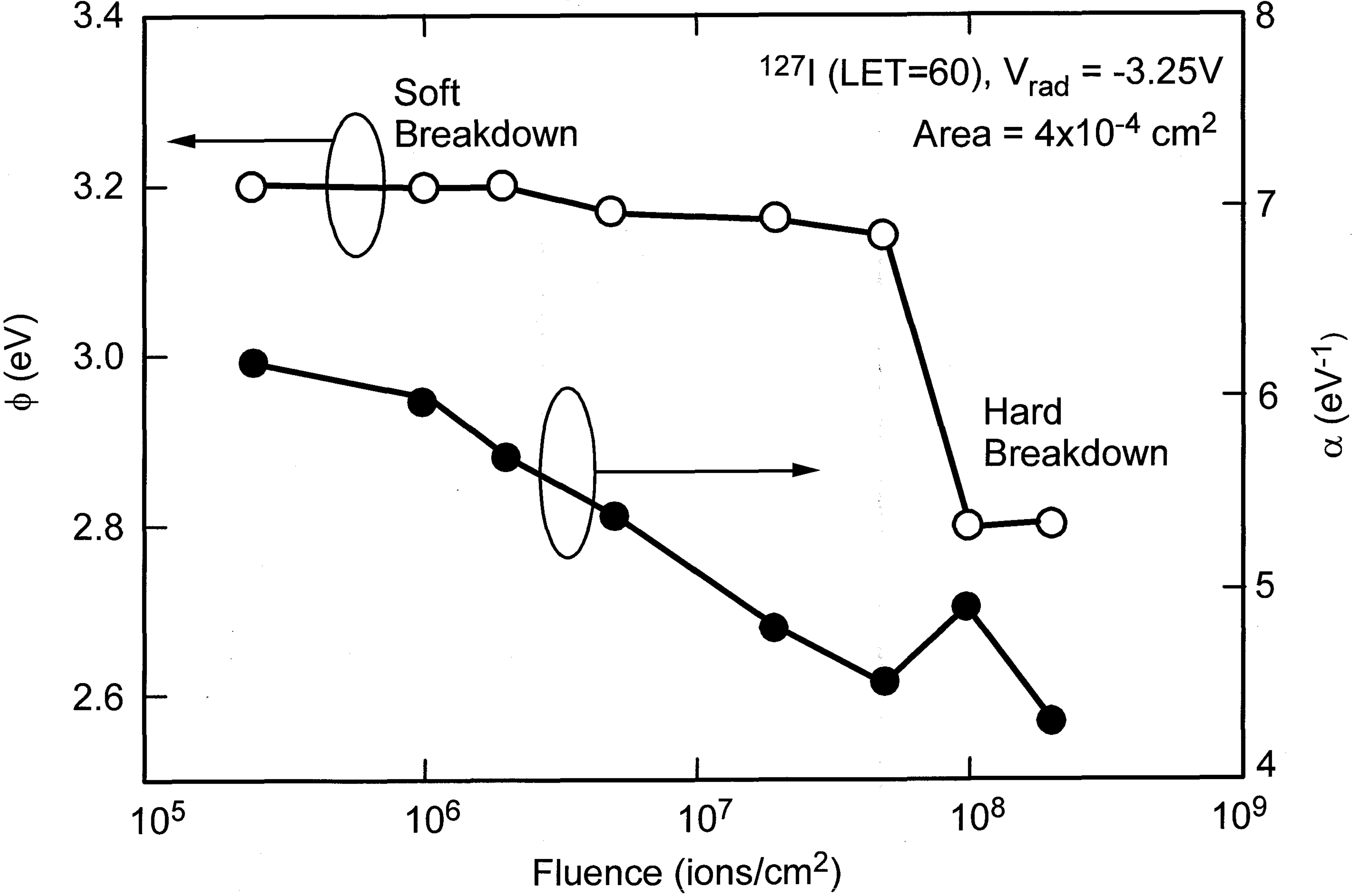
ϕ: $\propto$ Shape / Thickness (1/eV)

-J. Sune and E. Miranda, IEDM 2000.

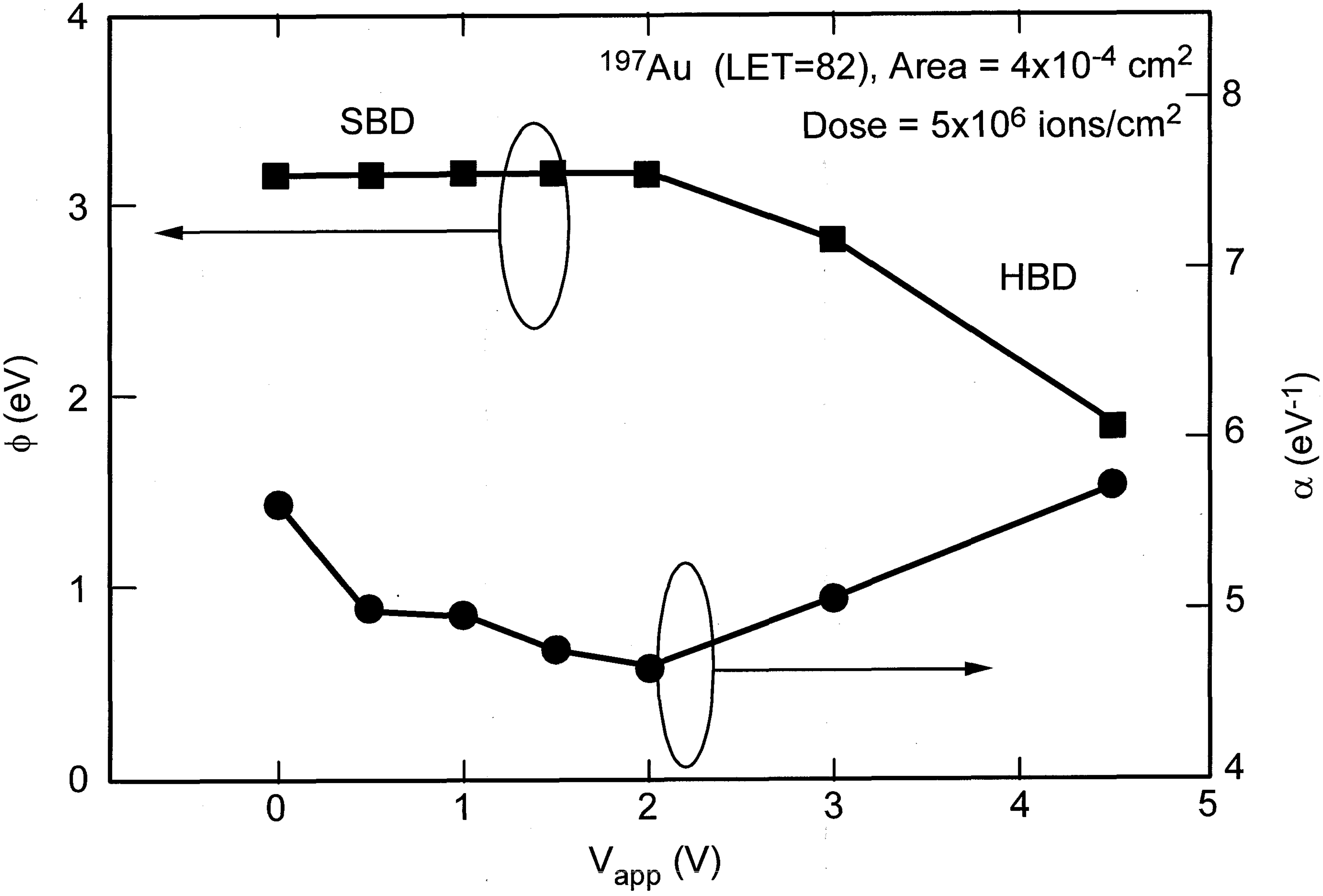
I_g-V_g *Curves as a Function of Fluence*



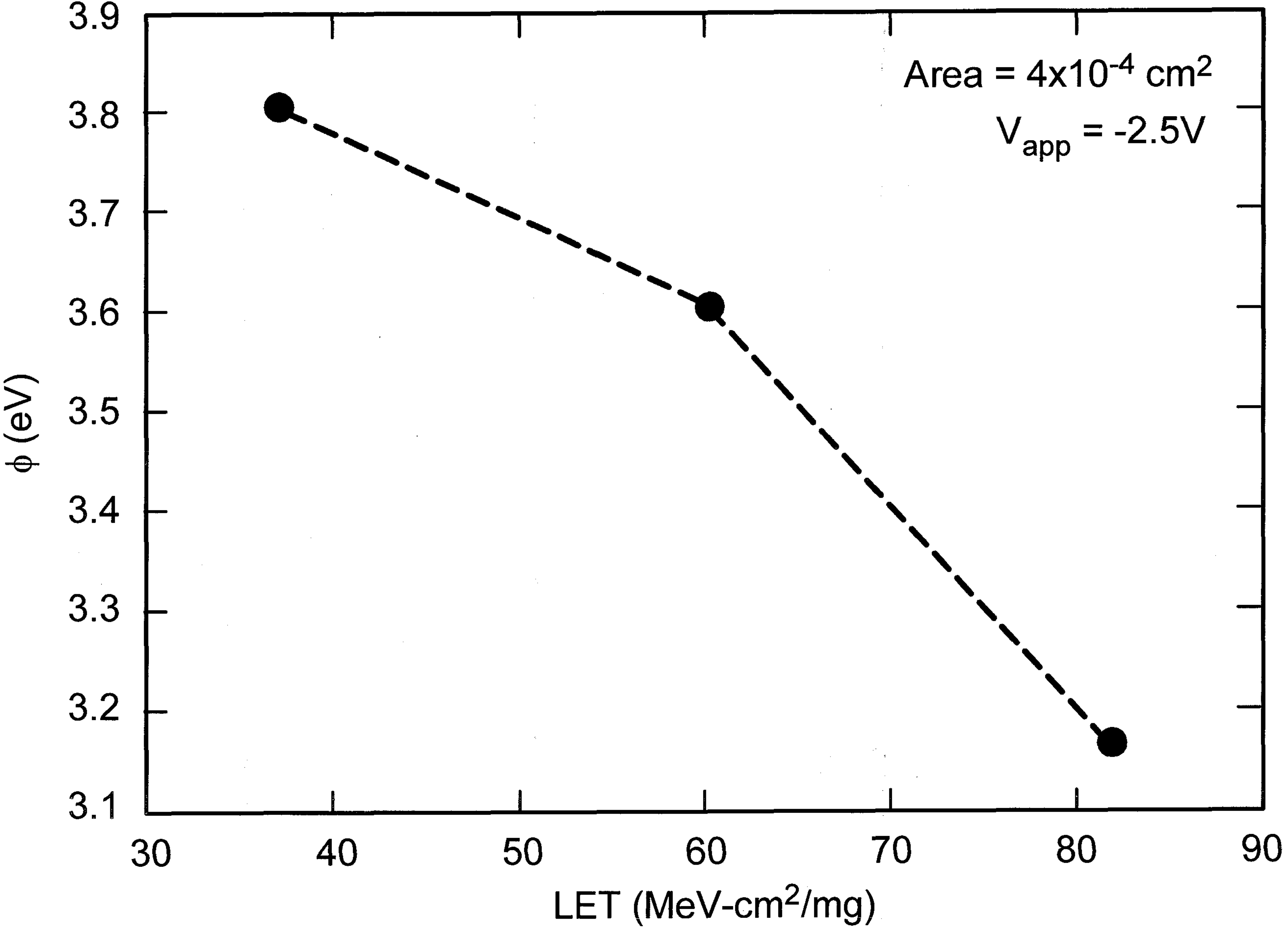
Extracted ϕ and α vs. Fluence



Extracted ϕ and α vs. V_{app}



Extracted ϕ vs. LET



Summary

1) Heavy ion induced leakage depends on LET, fluence, and V_{app} (in decreasing importance). Leakage scales with area.
2) RSB observed even at low fluence and zero bias.
3) For Au and I, SBD is followed by HBD at higher voltages.
4) Voltage for SEGR (HBD) decreases with LET.
5) Sune model fits data well:
   - α depends inversely on fluence and V_{app}.
   - ϕ depends inversely on LET.
6) Interpretation:
   - Size of path depends on LET and voltage.
   - Number of paths depends on fluence.

Conclusions

1) Field / voltage required for HBD outside realm of normal operation.

   - SEGR probably not a major concern for near future.

2) In reliability community, HBD not necessary for oxide failure. The first SBD is considered destructive and is used for lifetime projection.

   - RSB may therefore more properly be considered destructive.

3) The fact that RSB scales with area and can occur even at low fluence and zero bias is a cause for concern.

   - Powered down parts are not immune and systems with large areas may be more susceptible.

4) The degree of harm that RSB may cause will depend on the application. More work will be needed to determine whether RSB affects the long term reliability of the oxide and poses a threat to the future use of MOS devices in space.