Reverse-Bias Degradation of SiGe Transistors at Normal and Cryogenic Temperatures

Alexander Teverovsky/QSS Group, Inc.,
Ashok Sharma, Jeffrey Piepmeier /NASA, GSFC

Outline

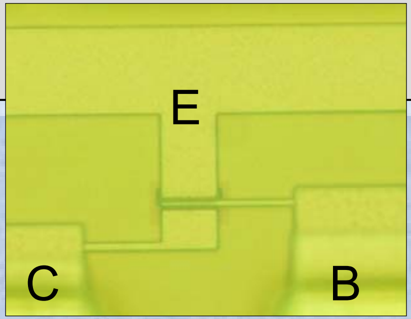
- Background.
- Experiment.
- Characteristics of SiGe transistors at room temperature (RT) and liquid nitrogen (LN) conditions (-196 ^{o}C).
- Effect of interim forward voltage measurements during reverse bias stress (RBS) testing at RT and LN.
- Environmental effect on RB degradation at RT.
- Effect of voltage on RB degradation at RT and LN conditions.
- Comparison of RB degradation at RT, –40, +125, and -196 ^{o}C.
- Conclusions.

Background

- Exposure to reverse EB voltages degrades low-current gain and increases noise in most BJT and in SiGe technology transistors in particular.
- Reverse bias conditions happen during operation of mixed signal devices manufactured by BiCMOS technology (opamps and ADCs).
- The effect is known for more than 35 years, but gains importance for sub-micrometer size transistors.
- The level of degradation depends on design and materials and have to be evaluated for new technologies.
- The effect of environmental conditions on reverse bias degradation has not been sufficiently investigated yet.

Experiment

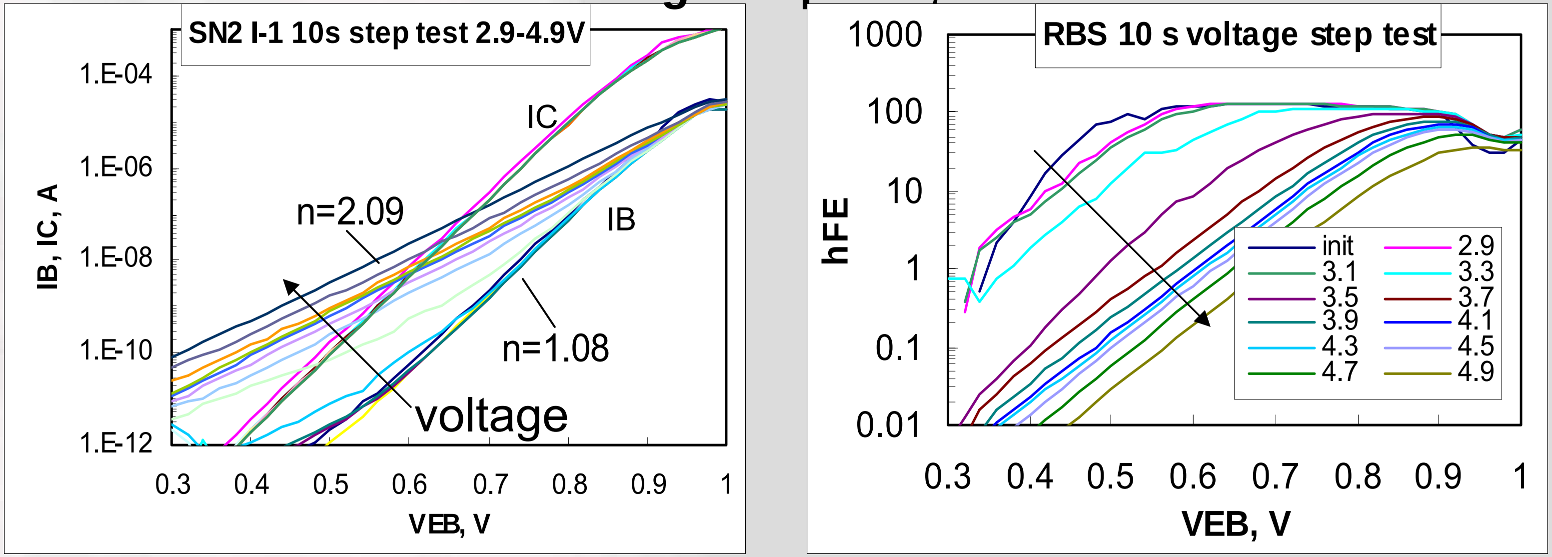
Test transistors are covered with polyimide



- Test transistors: SiGe NPN transistors manufactured by BiCMOS 0.35 μm technology. Emitter dimensions: 0.32×1.04 μm (gr. I), 0.32×2.5 μm (gr. II), 0.44×2.5 μm (gr. III), 0.32×10 μm (gr. IV), 0.32 μm × 5 μm (gr. V).
- Electrical measurements: Gummel plots and I-V characteristics were measured using a HP4156A semiconductor analyzer.
- RBS conditions: Transistors were stressed at room temperature, +125 °C, -40 °C, and -196 °C at open collector bias and E-B voltages varying from 2.5 V to 4.5 V during up to 1200 hrs in some cases. Reverse currents and Gummel plots were measured periodically during the test.

Typical Variations of Gummel Plot and Gain during RBS at RT

RB voltage step test, t=10 sec.



- Base current is a sum of diffusion and recombination components (the non-ideality factor n = 2 for recombination current)

$$IB = IB_{01}\exp\left(\frac{eV_{BE}}{kT}\right) + IB_{02}\exp\left(\frac{eV_{BE}}{n\times kT}\right)$$

- IC remains stable during RBS testing →

$$h_{FE}(0)\Big/h_{FE}(t) = IB(t)\Big/IB(0)$$

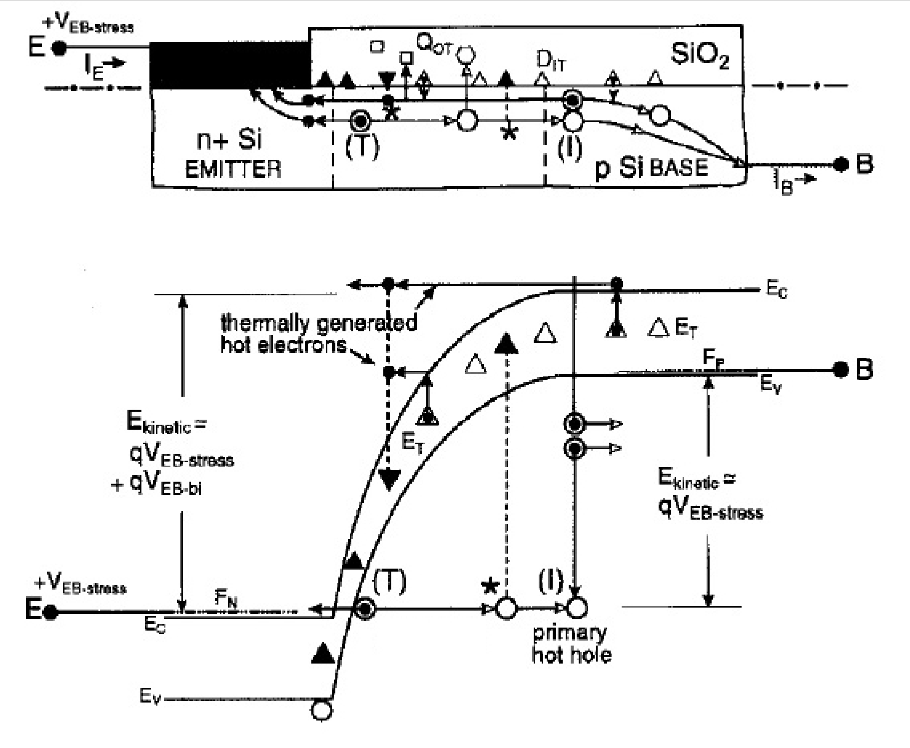
- Degradation is due to increased surface recombination.

Mechanism of RB Degradation

Commonly accepted model of RBS degradation includes:

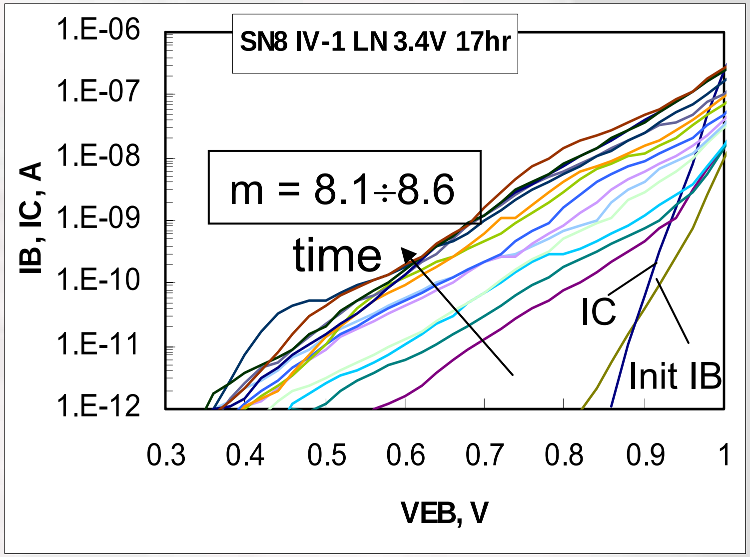
- generation of hot carriers (both, e^- and h^+) along the periphery of emitter;
- generation of traps at the Si/SiO2 interface of the E-B oxide spacer by hot carriers;
- increase in positive oxide charge as a result of hole trapping;
- increase of the base current due to surface recombination of carriers injected from emitter at newly generated surface states.

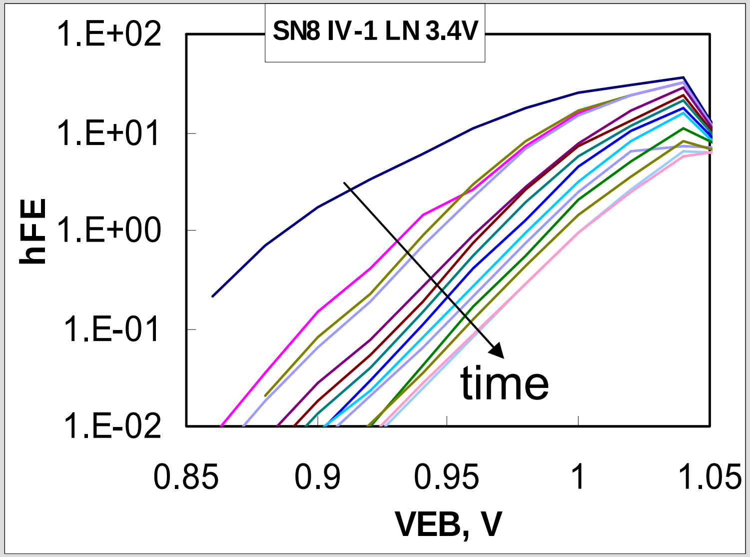
Formation of interface traps D_{IT} and oxide charge Q_{OT}



[A. Neugroschel, Chih-Tang Sah, M.S. Carroll, 1996]

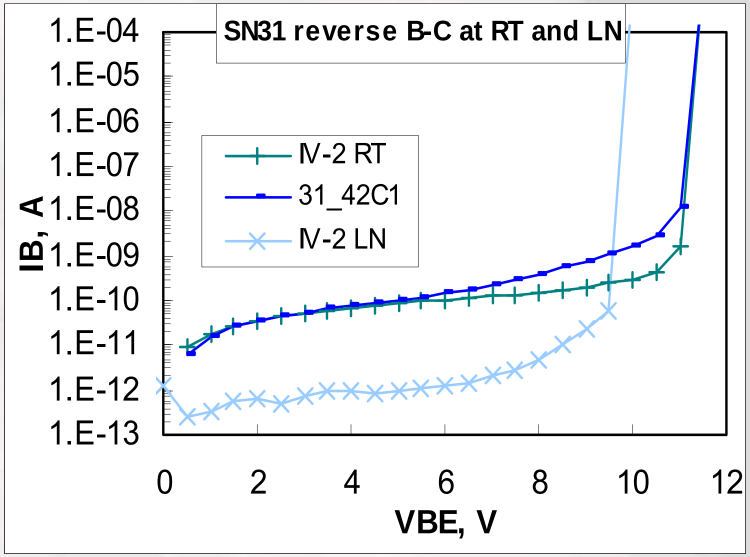
Gummel Plots and Gain Variations during RBS at -196 ºC

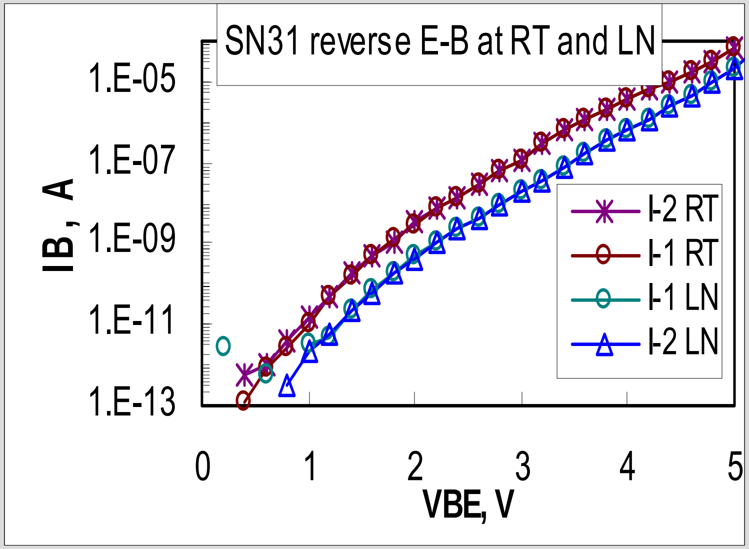




- The initial non-ideality factor changes from ~1 at RT to ~ 1.9 at LN.
- RB degradation at cryogenic temperatures appeared to be similar to RT; however, the non-ideality factors are anomalously large and cannot be explained by excessive recombination.
- Degradation mechanism at cryogenic temperatures might be different compared to room temperature conditions.

Effect of Temperature on CB and EB I-V Characteristics

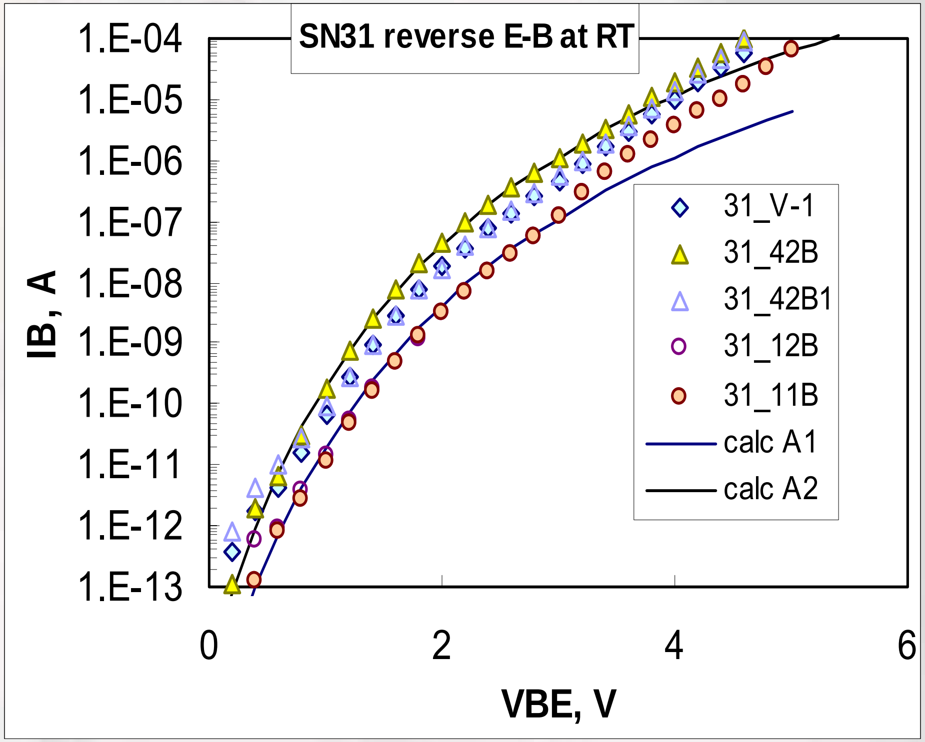




- Base-collector breakdown voltages decrease at -196 ^{o}C, thus indicating avalanche breakdown.
- Emitter-base reverse characteristics at low temperatures are shifted to higher voltages indicating Zener breakdown.

Reverse EB Characteristics

Experimental and calculated EB characteristics



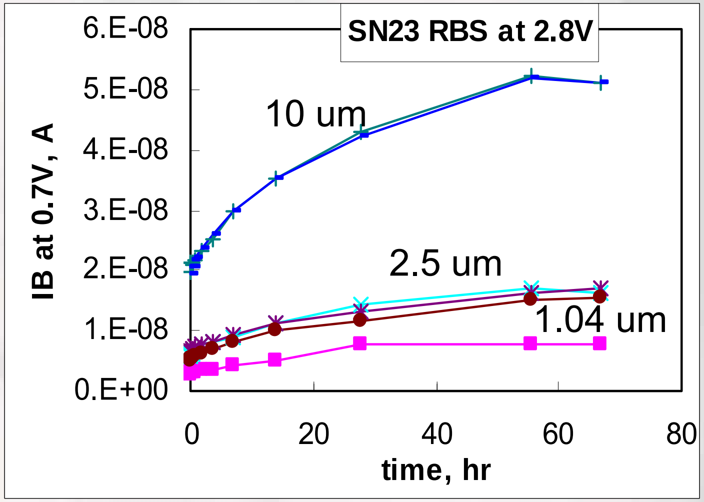
- Reverse EB I-V characteristics are reproducible and follow the interband tunneling rate formula:

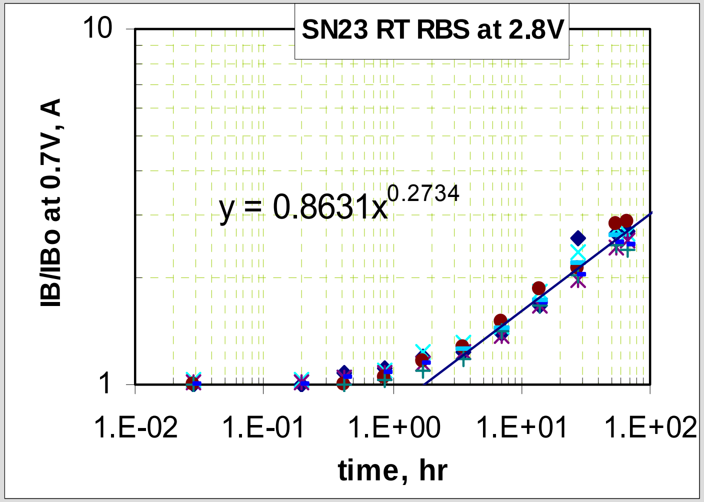
$$IB_R = A \times \exp\left(\frac{-B}{(V_{EB} + V_{bi})^{0.5}} \right)$$

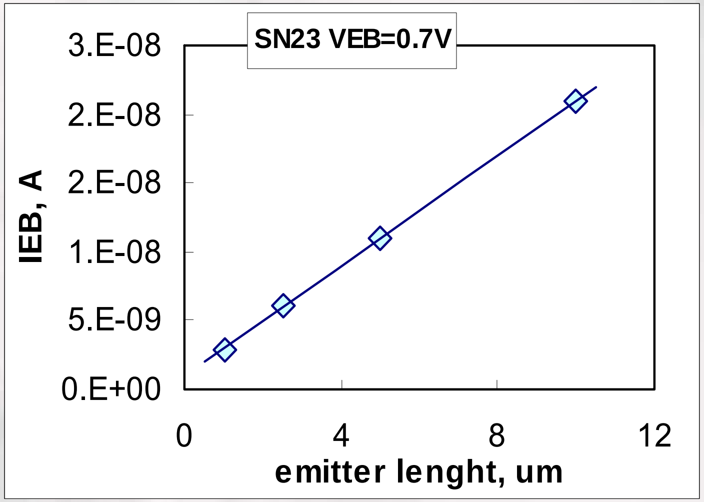
Where B – parameter (= 47.1); V_{bi} – EB built-in voltage (=1.2 V)

- Tunnel currents increase exponentially with maximum electrical field.

Effect of Emitter Size

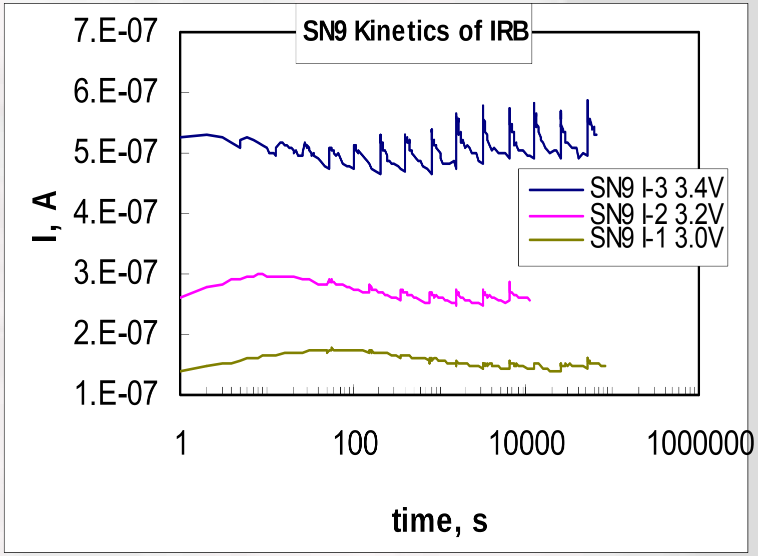


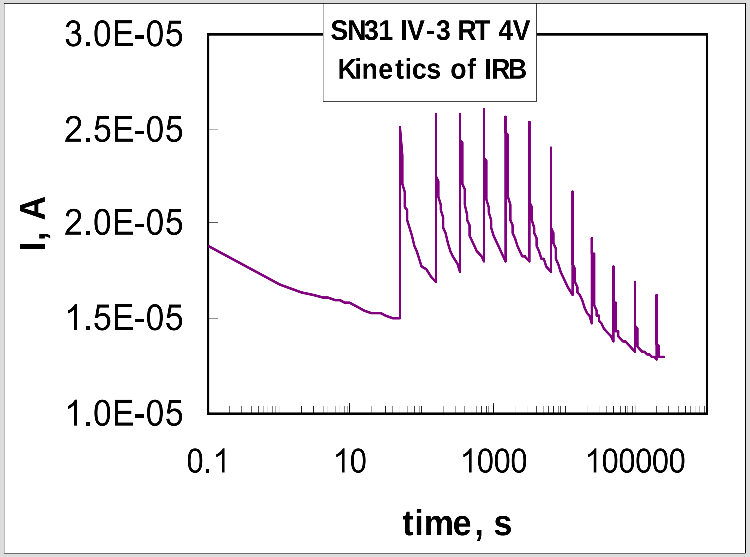




- Forward current is a linear function of emitter length;
- Normalized degradation does not depend on the size of emitter and follows a power law.

Effect of Interim Measurements during RBS at Room Temperature

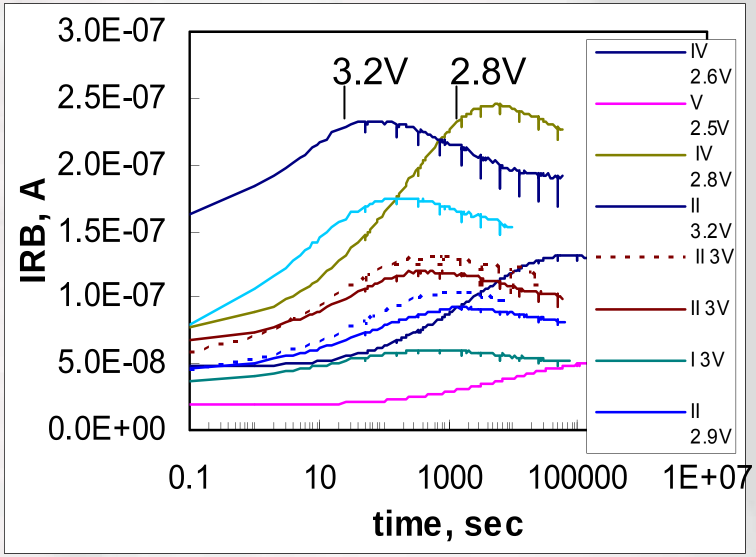




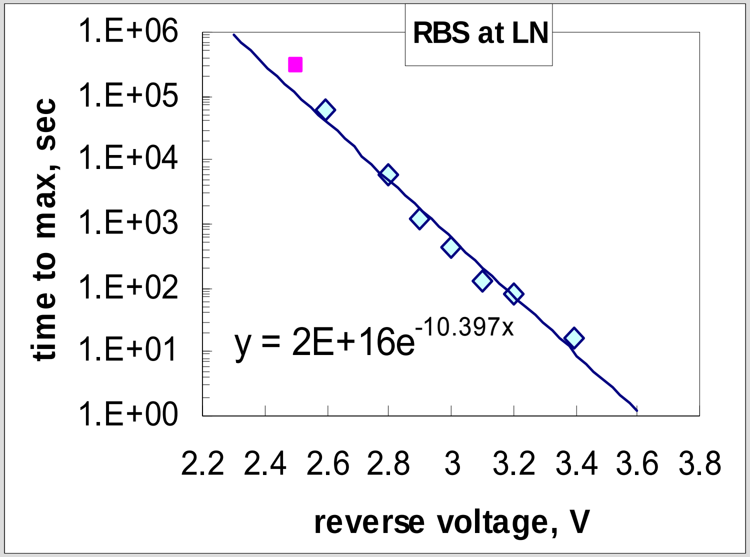
- Transients are caused by interruptions of RBS for forward current measurements.
- The transients develop with time of RBS and their amplitude increases with applied voltage.
- The effect is probably due to changes in SiO_2 surface charge caused by injected electrons.

Kinetics of Reverse Currents at -196 ^{o}C

Kinetics of reverse currents at V_{RB} = 2.5 to 3.2 V, T = -196 ^{o}C



Voltage dependence of time-to-maximum I_{RB} at -196 ^{o}C

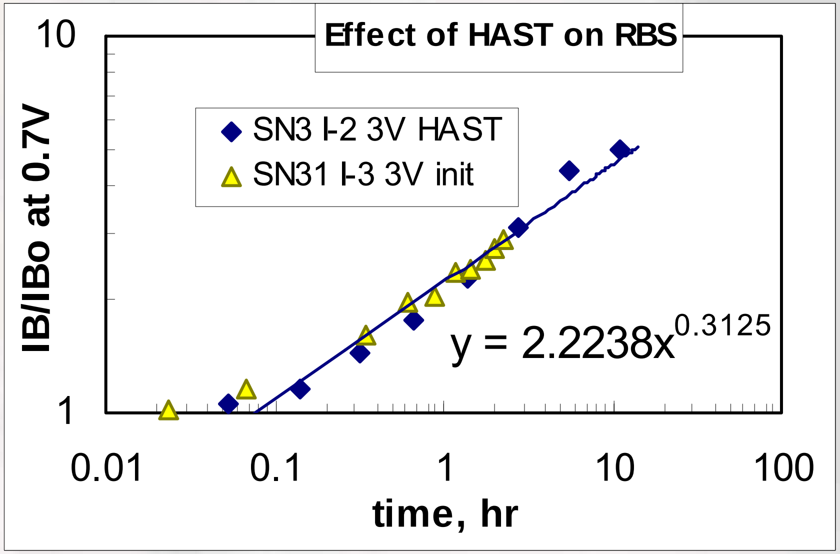


- Similar to what was observed at room temperature, at LN conditions the time-to-maximum reverse current decreases with voltage exponentially.
- Extremes in I_{RB} - t curves might indicate a change in the degradation mechanism.

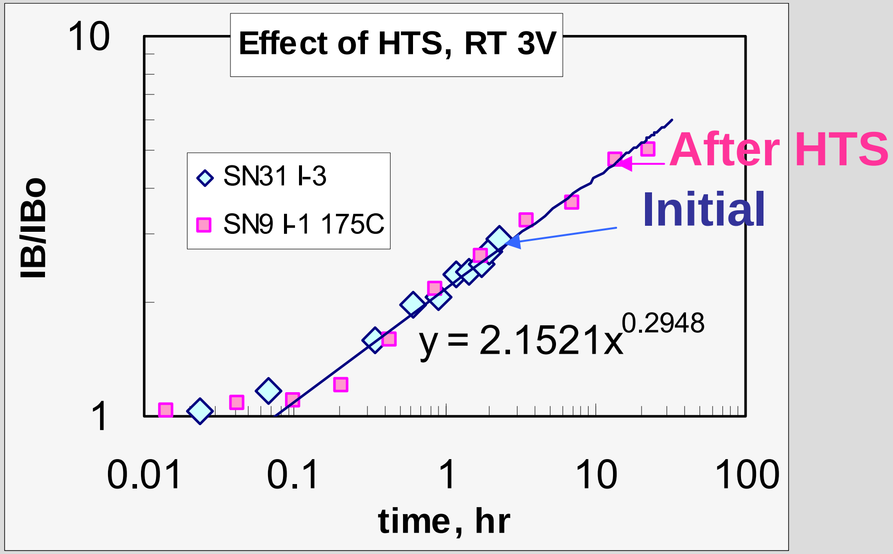
Effect of Environmental Stress Testing

Moisture in SiO_2 might affect degradation caused by hot carriers

HAST at 130 °C/85% RH/100 hr



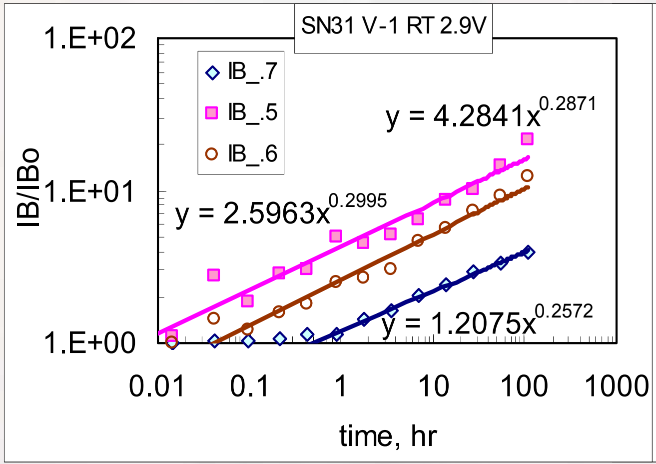
High-temperature storage at 175 °C

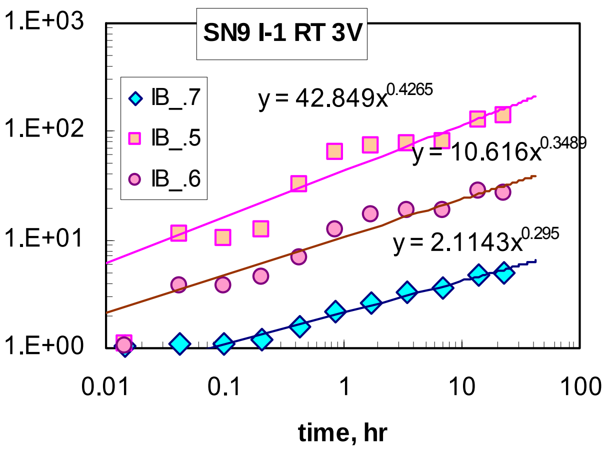


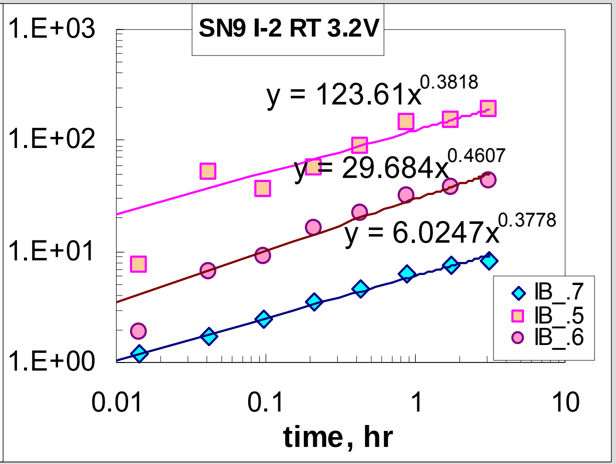
- No changes in RB testing after HAST at 130°C/85%RH/100hr and HTS at 175°C for 100 hrs.
- Environmental conditions do not affect results of RB testing probably due to Si_3N_4 passivation.

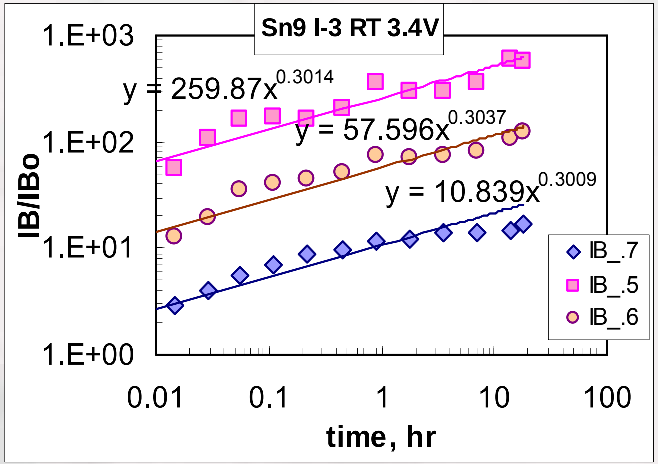
Effect of RB Voltage at RT

Base current variations measured at 0.5 < VF < 0.7V during RB testing at V_{RB} varying from 2.9 to 3.4 V









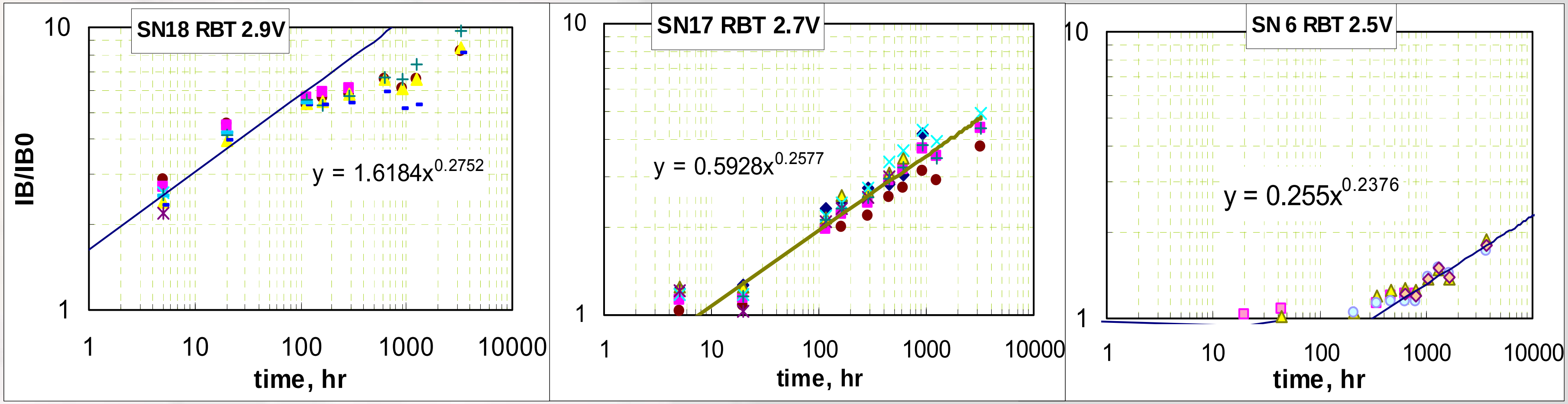
For a given V_{RB}, degradation measured at different VF follows a power law:

$$IB/IBo \sim t^{\beta}\ ,\quad t > t_i(VF)$$

where $0.25 < \beta < 0.45$, $t_i(VF)$ is the induction period increasing with VF.

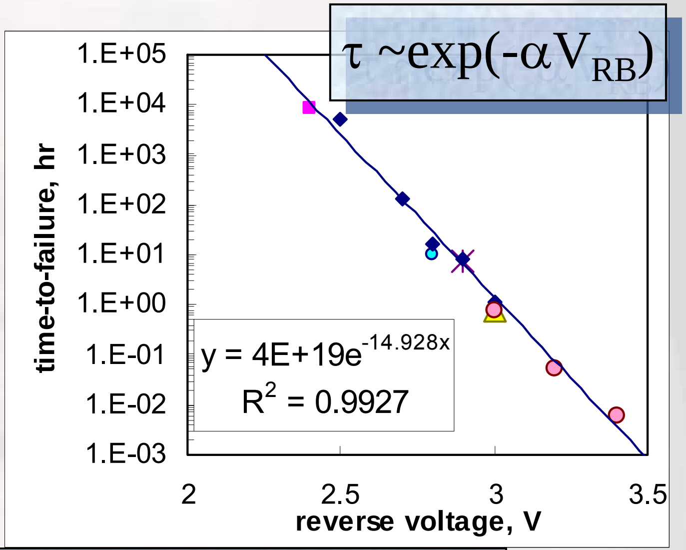
Effect of RB Voltage at RT (Cont.)

Base current variations measured at VF = 0.7V during RB testing at V_{RB} varying from 2.9 to 2.5 V



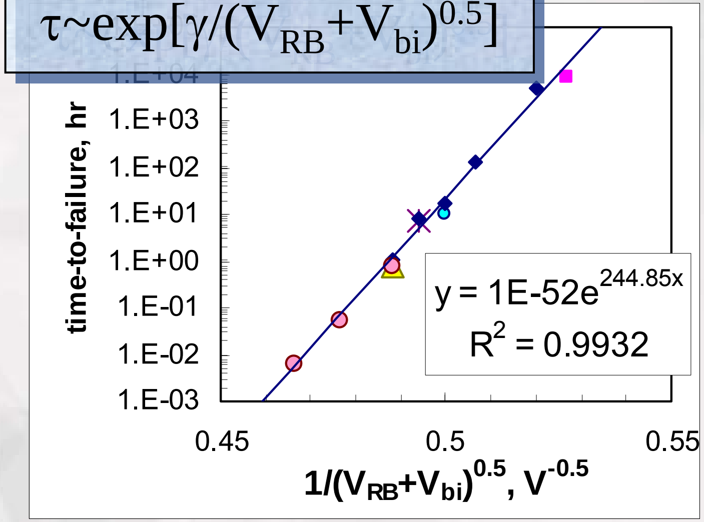
- At VBE = 0.7 V and 2.5 < V_{RBS} < 3.4 V the exponent β varies in a relatively narrow limits: 0.25 < β < 0.35 .
- At RB voltages <~3V degradation might saturate only after several hundred or thousand of hours of stress.

RB Degradation at Room Temperature



$\tau \sim \exp(-\alpha V_{RB})$

$\tau \sim \exp[\gamma/(V_{RB}+V_{bi})^{0.5}]$

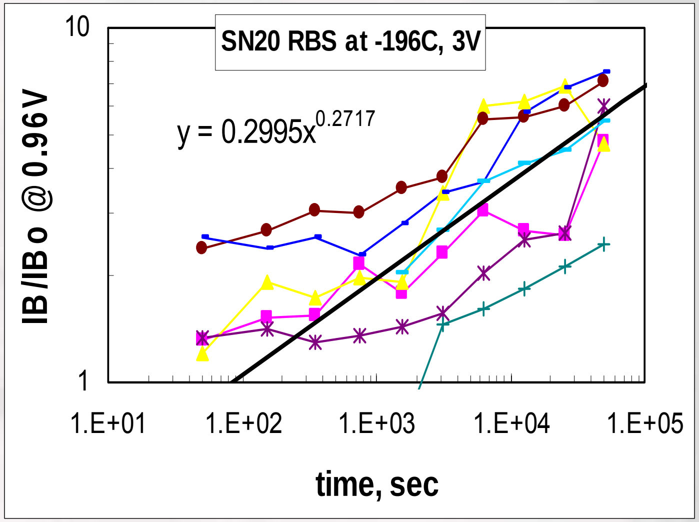


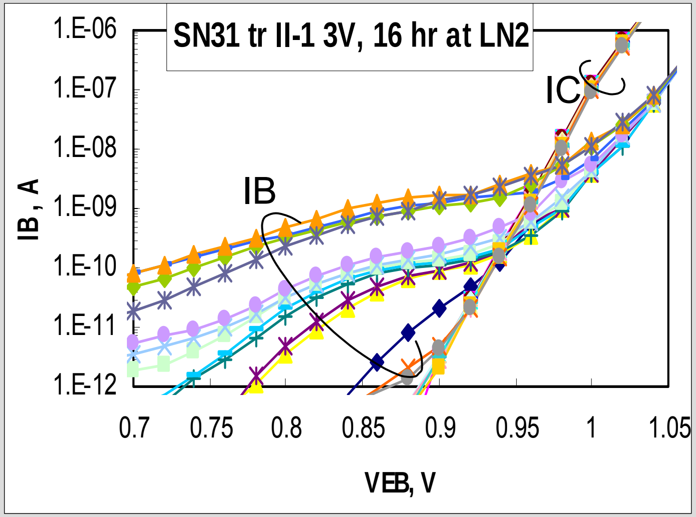
- Time-to-failure, τ, (time to IB/IBo=2 at VF=0.7V) was calculated based on test results at different V_{RB}.
- Experimental data fit well to both approximations: $\tau^{-1} \sim \exp(\alpha V_{RB})$ and $\tau^{-1} \sim I_{RB} = A\times\exp[B/(V_{RB}+V_{bi})^{0.5}]$
- It is possible that no degradation occurs below ~2 V as more than 2 eV might require to form a defect.
- Even low-voltage transient RB spikes at EB junction can cause degradation.
- Degradation can be described as:

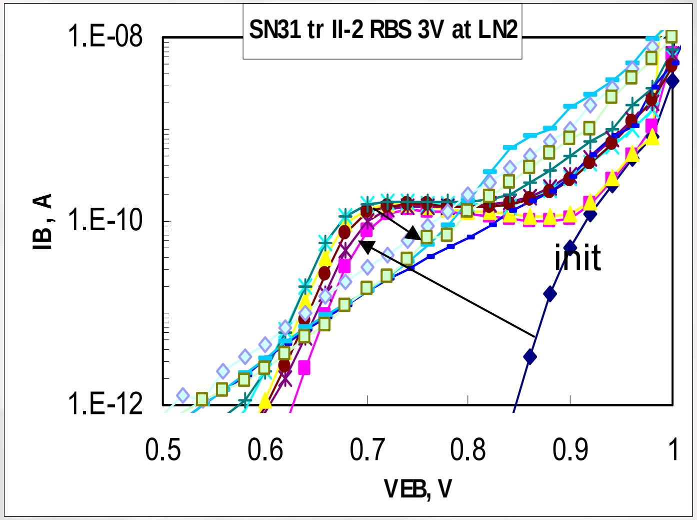
$$\frac{IB}{IB_0} = A \times t^{\beta} \times \exp\left(-\alpha \times V_{RB}\right)$$

where $\beta = 0.3$, $\alpha = 4.4$

RB Degradation at -196 ºC



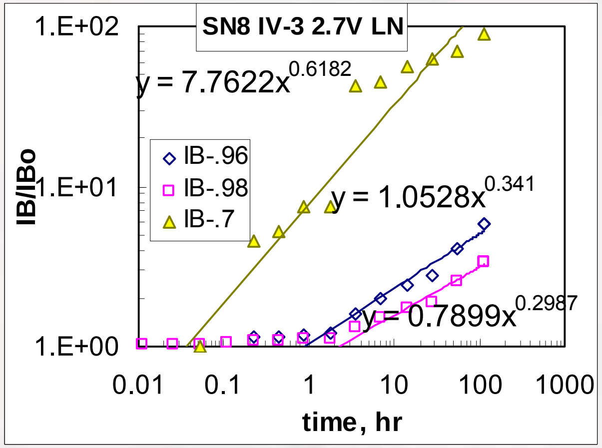


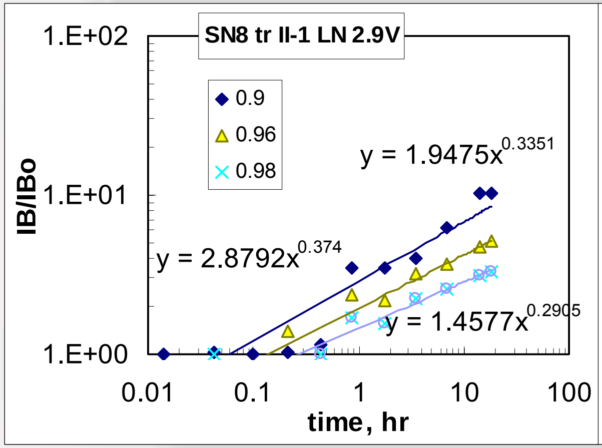


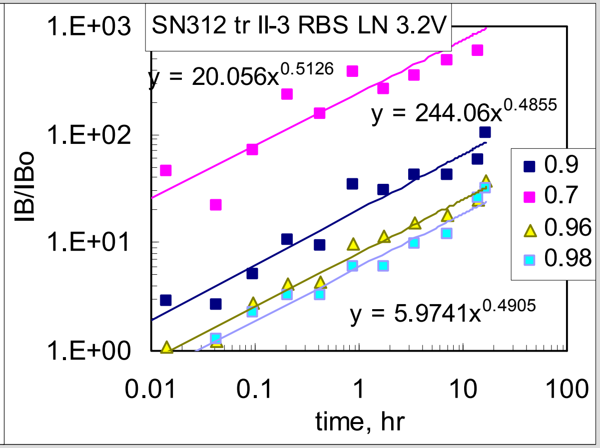
- Degradation at -196 ºC is less reproducible, than at room temperature.
- RBS resulted in anomalous behavior of forward I-V characteristics in some cases.

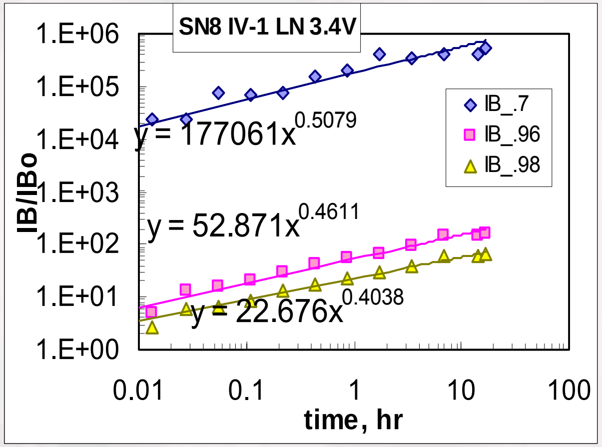
Effect of RB Voltage at -196 ºC

Base current variations at 0.7< VF< 0.98 V during RB testing at 2.5 ≤V≤ 4V









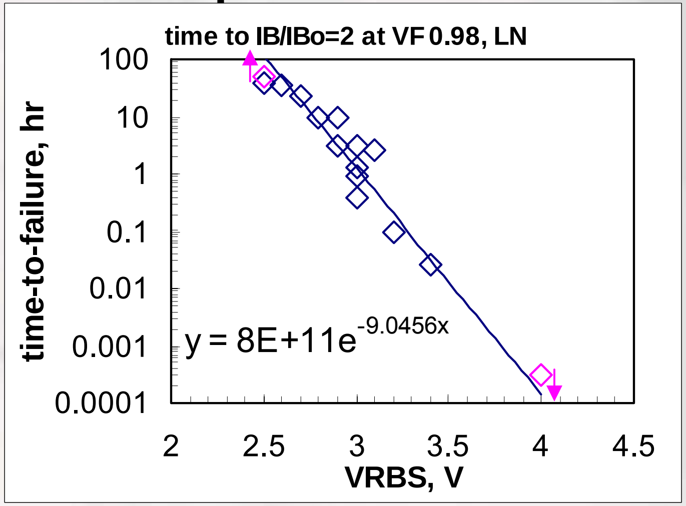
- Data scattering at LN is larger than at RT.
- Similar to RT conditions:

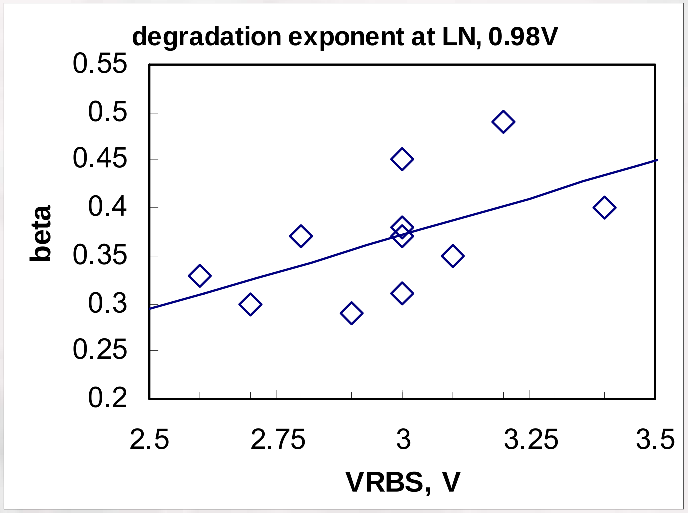
  $IB/IBo \sim t^{\beta}\ ,\ t > t_i(VF)$

  where $0.3 < \beta < 0.6$
- Degradation exponent, β, has a trend of increasing at lower VF and is somewhat larger than at RT ($\beta_{avr.}$~0.35).

Degradation at -196 ºC

Experimental data





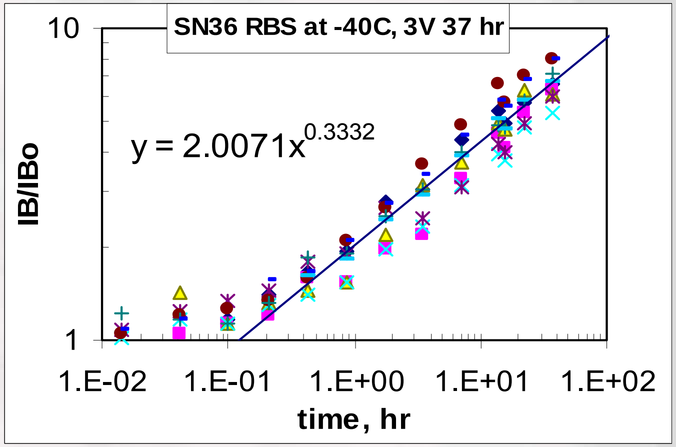
- Time-to-failure, τ, (time to IB/IBo=2 at VF=0.98V) is an exponential function of V_{RB}; however, the exponent is lower than at RT.
- Experimental data fit well to both model [$\tau \sim \exp(-\alpha V)$ and $\tau^{-1} \sim IR$]
- The exponent in $\tau(V_{RB})$ is close to the exponent in time-to-maximum I_{RB} vs. V_{RB}.
- Degradation at -196 ºC can be described similarly to RT:

$$\boxed{IB / IB_0 = A \times t^{\beta} \times \exp\left(-\alpha \times V_{RB}\right)}$$

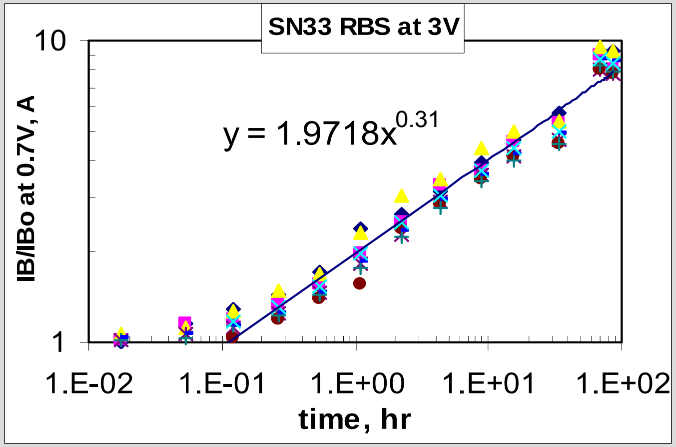
where $\beta = 0.35$, $\alpha = 3.2$

RB Testing at –40, +25, and +125 ^{o}C

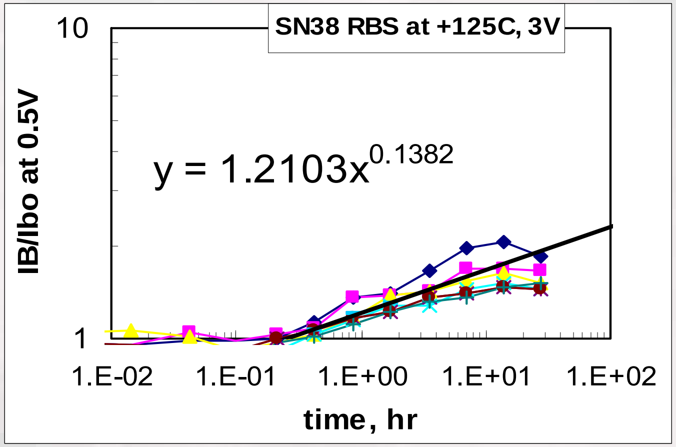
Results at -40 ^{o}C



Results at RT



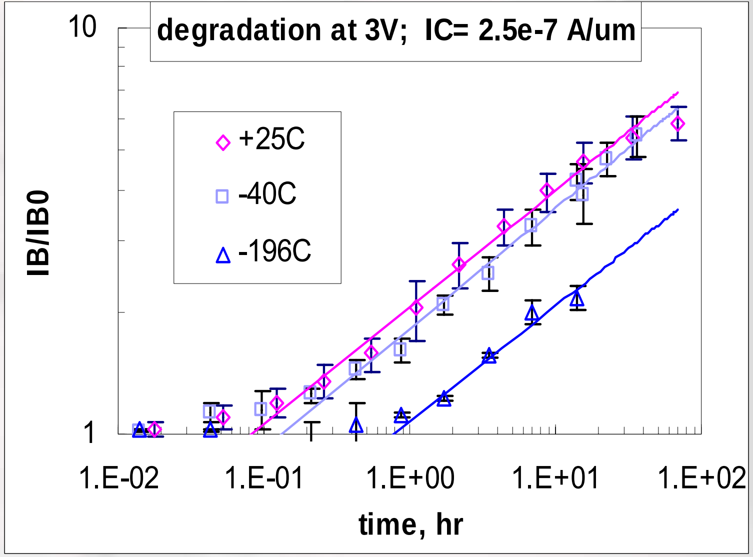
Results at +125 ^{o}C



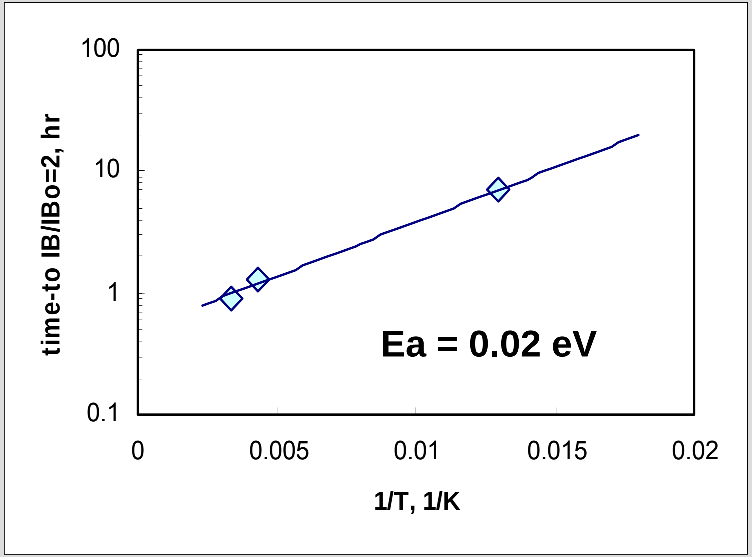
- Degradation at -40 ^{o}C is similar to degradation at RT.
- Degradation at +125 ^{o}C is much slower than at RT and has a trend of saturation after a few hrs.
- Results at 125 ^{o}C are likely due to decrease in the tunnel component of reverse current, rather than to annealing.

Temperature Dependence of Time-to-failure

RBS at 3V. Degradation is normalized to IC = 2.5×10^{-7} A/μm



Arrhenius plot of time-to-failure (IB/IBo = 2)



- In the range from +25 ^{o}C to -196 ^{o}C RB degradation normalized to IC=2.5×10^{-7} A/μm follows power law with an exponent β ~ 0.3.
- At VBR~3V and temperatures from RT to LN the time-to-failure has a weak temperature dependence with Ea ~0.02 eV.
- There is a trend of further decreasing of Ea with VRB down to ~ -0.04 eV at VRB = 2.5V.

Conclusions

- Temperature dependence of I-V characteristics indicates that reverse currents of EB junctions are due to the tunnel effect.
- After RB testing the non-ideality factor of EB I-V characteristics at RT, n, is close to 2 suggesting that degradation was due to increased surface recombination along the periphery of emitter.
- At -196 °C, n is anomaly large (n> 8) indicating that at cryogenic temperatures the tunnel mechanism might prevail even at forward bias conditions.
- Interim forward E-B current measurements during RBS result in transients of reverse currents and change the level of degradation.
- Kinetics of reverse currents at RT and -196 °C features extreme dependence on time and the time-to-maximum exponentially decreases with the applied voltage.
- RB degradation at –40 °C is similar to room temperature conditions and follows a power law, IB/IBo ~ t^{β}, where $0.25 < \beta < 0.45$.

Conclusions, Cont’d

- At 125 ^{o}C degradation occurs much slower, than at RT and has a trend to saturate after a few hours of stress.
- Degradation at -196 ^{o}C features erratic behavior and results in anomalous forward EB I-V characteristics in some cases. However, on average RB degradation can be also described with a power law.
- At 2.5 < V_{RB}< 4 V and temperatures from +25 to –196 ^{o}C RB degradation can be described using a simple model:

$$\boxed{IB/IB_0 = A \times t^{\beta} \times \exp\left(-\alpha \times V_{RB}\right)}$$

, where $\beta \sim 0.3$, $\alpha \sim 4.4$ at RT and $\beta \sim 0.35$, $\alpha \sim 3.2$ at LN

- In the range from +25 ^{o}C to -196 ^{o}C, the time-to-failure has a weak temperature dependence with an apparent activation energy $-0.04 < Ea < 0.02$ eV.