ESTIMATING THE POWER BJT EXCESS CHARGE RECOMBINATION TIME CONSTANT

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Abstract: The paper demonstrates an experimental way of estimating the excess minority carriers charge stored within the the power bipolar transistor in the saturation mode, i.e. with both junctions forward-biased, as a reference to future IGBT switching action analysis. The method is based on analyzing the transient turn-off base current waveforms at different conditions right before this event. The base current is known to supply the minority carriers within the device. Estimating the recombination time constant serves as a basal precondition for further identification of the excess charge storage depending on various operating conditions and retrospectively an accurate identification of power BJT and IGBT various partial stage of switching action.

Keywords: power BJT, IGBT, saturation, excess charge storage, switching process measurement

1 INTRODUCTION

Knowing the excess minority carriers concentration within power BJT collector N-drift and base region, i.e. the amount of stored charge, during on-state (Fig 1) or simply the depth-of-saturation is not so crucial any more, nor in the case of intrinsic BJT of still widely used IGBTs. However, the

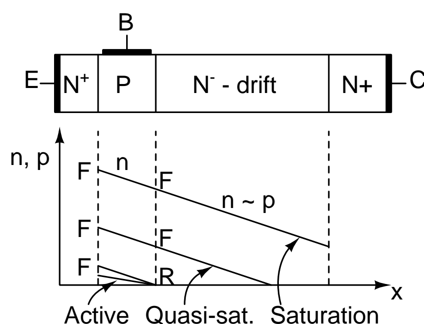

Figure 1: Simplified one-dimensional structure of power BJT. The geometry is illustrative i.e. not proportional to the real device dimensions. Also the concentrations within base and collector don't share the same scale (concentration gradient is kept constant to highlight its proportionality to shared collector current - pure diffusion current in saturation)

excess charge storage does not define only the static saturation characteristic, but also has significant impact on the switching speed and switching waveforms shape. Therefore, it is useful to have some quantitative information about this charge for switching action analysis and modeling as well as for ability to implement the advanced IGBT driving techniques [1], [2]. It is, however, not possible to measure the stored charge straightway, neither from device saturation characteristic nor the switching waveforms, especially in IGBT case, as it does not provide access to the intrinsic BJT terminals.

Access to BJT base current is crucial for the targeted task as it is known that excess minority carriers are supplied by the base current. Likewise, the charge can be deflated by the negative base current, as is the case of switching-off action of the transistor. The time integral of negative base current during turn-off event provides an information about the charge deflated by the base current - i.e. the steady-state excess charge right before the event.

Therefore, the use of an "archaic" power BJT for the reference purpose is highly beneficial as it provides the direct access to the base current by means of both measurement accuracy and controllability of waveform shape and parameters. Those observations common among the power BJT and intrinsic BJT within IGBT may be further applied to IGBT analysis.

Prior to other experimental charge storage analyses one need to eliminate the impact of charge recombination within transistor, because this charge is not reflected in the base current waveform. That means to use such conditions (current levels and switching time) that the recombined charge portion is provably negligible compared to that deflated by the negative base current or alternatively to quantify and account the recombination effect.

This is why it is very convenient to estimate the recombination time constant first. Next sections describe an experimental method of such estimation.

2 THEORY

From general semiconductor device physics, the amount of stored charge Q supplied by the current I and kept down by recombination with characteristic time constant τ [3] is described by the *charge control equation* [3] [4]:

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = I - \frac{Q}{\tau} \tag{1}$$

Knowing the initial conditions (zero charge at zero time), the solution is:

$$Q = \tau I \left(1 - e^{-t/\tau}\right) \tag{2}$$

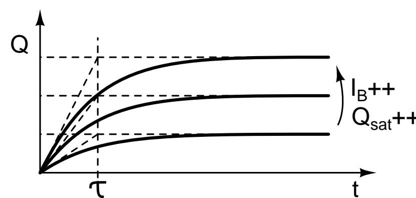

Figure 2: The stored "saturation" charge evolution with time, supplied by a constant base current and recombined with recombination time constant τ.

Here, the term τI can be denoted as saturation (steady state) charge Q_{sat}. A few findings can be implied from the solution (2) - also depicted in Fig. 2:

- The amount of steady state stored charge Q_{sat} is proportional to supply current. This is also apparent from the charge control equation (1) considering $\frac{\mathrm{d}Q}{\mathrm{d}t} = 0$ in steady state.
- In ideal case, time constant of exponential growth of charge is independent on supply current. In reality, especially in the case of power semiconductor devices, the time constant is dependent on level of injection [5], which is dependent on PN junction bias (and hence the current level).

3 METHODOLOGY

3.1 ASSUMPTIONS AND EXPERIMENTAL LIMITATIONS

The excess charge stored within lightly doped N-drift region in collector is essential for transistor saturation and forms the main portion of total stored charge supplied by the base current. A principally small base width and higher base doping (compared to collector) and hence the majority carriers concentration allows neglecting the base charge contribution to the total excess charge.

The base current is known to consist of multiple components, while only the hole current flowing into the collector I_{pC} supplies the minority excess charge there. Again, I_{pC} is the main portion of total base current, approximately β-times higher than hole current supplying the base charge and it is particularly proportional to the base current I_B magnitude.

The equation (1) can now be applied to charge storage within collector as follows:

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = i_B(t) - \frac{Q(t)}{\tau} \tag{3}$$

which yields the solution of exponentially rising charge $Q(t)$ in case of constant $i_B(t) = I_{B+}$ as illustrated on Fig. 2 and steady-state charge theoretically equal to:

$$Q_{sat} = I_{pC} \cdot \tau \approx I_{B+} \cdot \tau \tag{4}$$

There are two obstacles in the intention to measure this exponential charge collection:

- Its growth i.e. the instant value is not possible to be measured directly. One can only obtain the projection of the previous steady-state charge by time integration of the negative (charge deflating) transient turn-off base current $i_{B-}(t)$.
- Even the obtained steady-state charge projection $Q_{sat,m}$ ("m" stands for "measured") is not necessarily credible quantity as it is always the difference between the actual stored charge Q_{sat} and the portion of charge that already got recombined. This can be expressed from "discharging" analogy to (3) after integration as:

$$Q_{sat,m} = \int i_{B-}(t)\,\mathrm{d}t = Q_{sat} - \frac{1}{\tau}\int Q(t)\,\mathrm{d}t \tag{5}$$

  This relation puts the practical presumption for the reasonable measurement: the magnitude of i_B, i.e. I_{B-} must be significantly greater than Q_{sat}/τ.

The charge control equation (3) is valid for collector charge in saturation mode only. The measurements were performed with open collector to satisfy this condition even at low I_{B+} levels (e.g. 200 mA). The consequences are as follows:

- saturation guaranteed even at low I_{B+} levels. Collector potential during on-state is always at the base potential plus approximately junction built-in voltage as the base-collector junction is forward biased or in equilibrium, never reverse biased. So, the active mode is excluded.
- Zero collector current $I_C = 0$. Side-effect of this condition is theoretically constant excess charge profile within collector (and base), the gradient pictured on Fig. 1 is zero, which maximizes the amount of stored charge at given I_{B+} thus increasing the measurement accuracy.
- Any "side" outflow of charge via collector terminal is excluded.

3.2 TEST SUMMARY

Based on above analysis, the following test procedure was proposed (all measurements are based on steady-state stored charge Q_{sat} projection into a charge-deflating negative base current waveform ($Q_{sat,m} = \int i_{B-}\,\mathrm{d}t$) at varying conditions:

- **Determining suitable** I_{B+} by varying I_{B+} at constant I_{B-}.
  Linear dependency $Q_{sat} = f(I_{B+})$ is expected, according to (4): $Q_{sat} \approx I_{B+} \cdot \tau$.
  However, the charge-deflation time increases for increased Q_{sat} at constant I_{B-}, so the recombined charge portion becomes non-negligible and the resulting characteristic $Q_{sat,m} = f(I_{B+})$ should flatten at higher I_{B+} values, according to (5).

- **Determining suitable** I_{B-} by varying I_{B-} at constant I_{B+}.
  Constant I_{B+} yields a **constant** Q_{sat} according to (4): $Q_{sat} \approx I_{B+} \cdot \tau$.
  However, the charge-deflation time for constant Q_{sat} increases with decreasing I_{B-}, so the recombination effect begins to apply and the resulting characteristic $Q_{sat,m} = f(I_{B+})$ should tend to zero at low I_{B-} levels.

- **Determining τ itself** by varying the total "charging" on-time T_{on}at constant I_{B+}.
  This is by all means the key measurement and also the key idea of test. Despite impossibility to measure the transient alternation of the successively growing charge, it is possible to compose such waveform by collecting individual steady-states and quasi-steady-states matching the desired time instant of transient waveform. Gradual shortening of charging time T_{on} approaches the margin of steady state / saturated charge and enters the quasi-steady-state region i.e. the not-fully "charged" stages. Triggering the turn-off event at any charging process stage gives the projection of charge status at instant right before the event, i.e. the status at time T_{on} after beginning of charging process. This allows the reconstruction of transient waveform by multiple steady-state measurements.
  Exponential growth with time constant τ is expected according to (3), (2) and Fig. 2. Important requirement here is to ensure the equality among Q_{sat} and $Q_{sat,m}$ as proposed by above test steps.

3.3 TEST BENCH

All testing was performed on test bench built for fast switching measurement of power semiconductor devices with minimized parasitic influences as described in [6] in detail.

The device under test - power BJT BUV48A - was driven by discrete base driver through a variable base resistor to provide a constant I_{B+} during whole "charging" on-state period T_{on} as defined on Fig. 5. Separated current path and base resistors were ensured for I_{B+} and I_{B-} via diodes.

As explained before, the collector was left open-circuited.

4 MEASUREMENT RESULTS

All of the measured waveforms show a very long base current tail i.e. a slow decay of negative base current after the constant I_{B-} phase. The long current tail is caused by open collector test condition, zero collector current, constant collector excess charge profile and subsequent slow flattening of base-emitter junction voltage - slowing down the charge deflation by decreasing the negative base current magnitude. This is definitely not a real operating state, but there is no restriction of utilizing it for test purpose.

4.1 DETERMINING SUITABLE I_{B+}

The measured characteristic $Q_{sat} = f(I_{B+})$ on the right-hand side of Fig. 3 validates the expectations introduced in section 3.2.

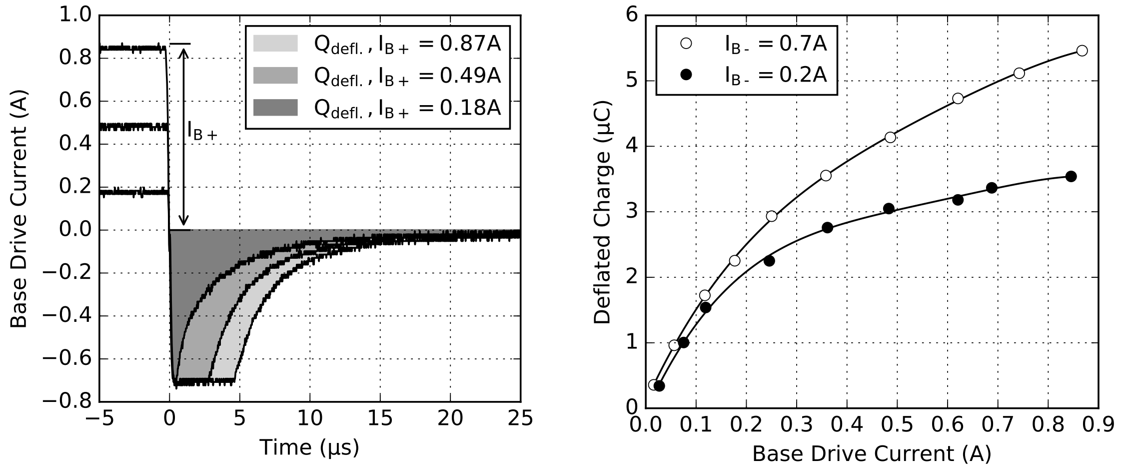

Figure 3: Deflated charge as a function of base drive current I_{B+}.

The transient waveforms plotted on the left side of Fig. 3 show the increasing charge-deflation time with increasing charge. The total deflation time increase is not crucial by means of recombination charge amount, because most of the current tail runs after the deflation of major portion of total charge. Essential is the time increase of constant I_{B-} phase, as it begins at full charge volume, i.e. at high recombination rate given by Q/τ.

The linear region independent on negative I_{B-} is valid only at current levels of $I_{B+} < 0.2\,\mathrm{A}$. This is again not a real operating state, where a large I_C decreases the steady state charge.

4.2 DETERMINING SUITABLE I_{B-}

The measured characteristic $Q_{sat} = f(I_{B-})$ on the right-hand side of Fig. 4 validates the expectations introduced in section 3.2.

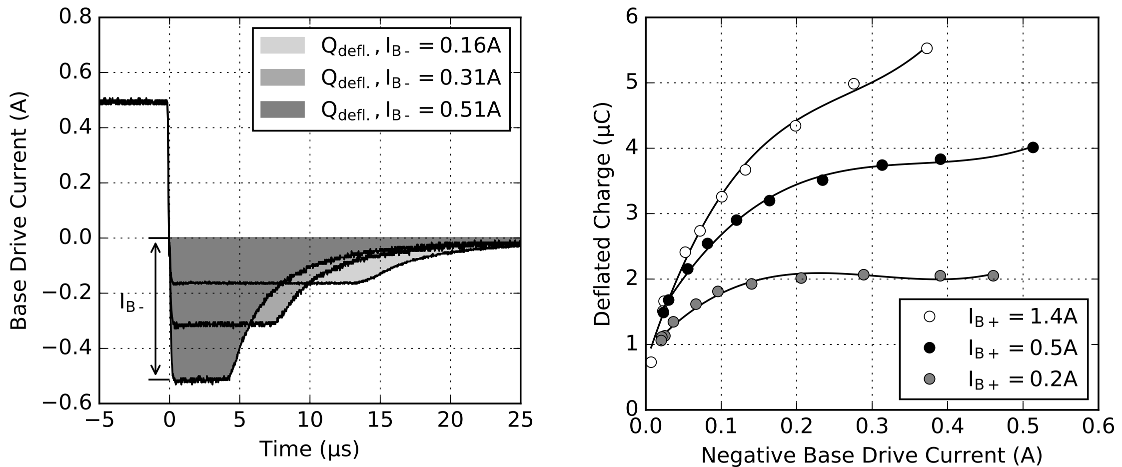

Figure 4: Deflated charge as a function of negative base drive current I_{B-}.

The waveforms on the left-side picture explain the increasing deflation (and high-level recombination) time with decreasing I_{B-}.

The recommended I_{B-} value for further testing at negligible recombination effect can be read from Fig. 4 to be $I_{B-} > 0.5\,\mathrm{A}$, depending on particular test conditions.

To be noted, the magnitude of I_{B-} on Fig. 4 does not reflect the amount of total stored charge, i.e. it is not proportional to recombination rate at given time instant. The total charge is defined by I_{B+} at the beginning of deflation process and continuously decreases with time progress with deflation rate ("speed") defined by I_{B-} level.

4.3 DETERMINING τ

The measured characteristic $Q_{sat} = f(T_{on})$ on the right-hand side of Fig. 4 reflects the transient growth of stored charge within base and collector as introduced in section 3.2.

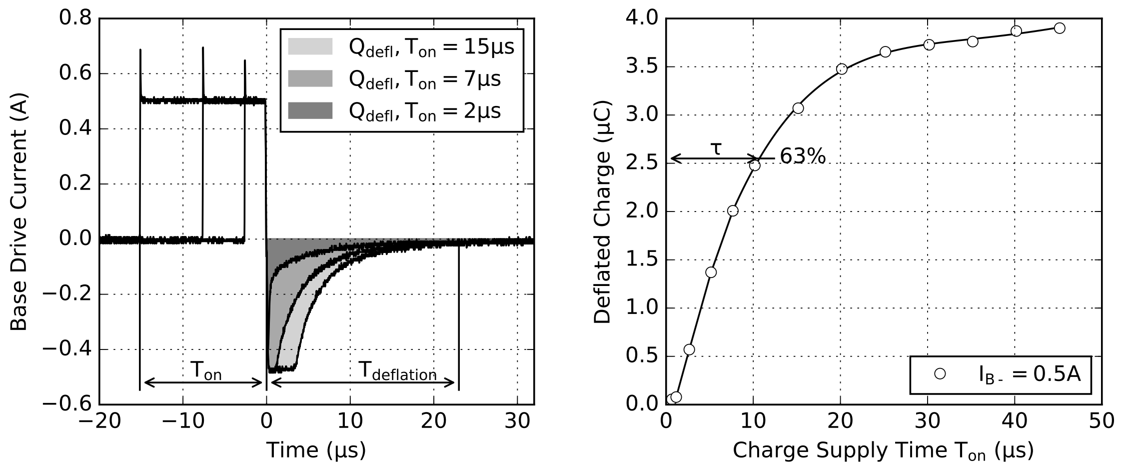

Figure 5: Deflated charge as a function of charge supply time T_{on}.

The time constant can be estimated from provided graph as time instant at which the charge reaches 63 % of steady state value:

$$\tau \approx 11\,\mu\mathrm{s} \tag{6}$$

It can be approximately verified by simple computation based on steady state relation (4) after substituting $Q_{sat} = 2\,\mu\mathrm{C}$ and $I_{B+} = 0.2\,\mathrm{A}$ conditions from right-hand side graph on Fig. 4:

$$\tau = \frac{Q_{sat}}{I_{B+}} \approx \frac{2}{0.2}\,\mu\mathrm{s} \tag{7}$$

5 CONCLUSION AND FUTURE WORK

The estimation method introduced in section 3.2 was experimentally verified as summarized in section 4. All of the test results match the theoretical expectations.

The estimation of recombination time constant enables further application of similar experimental method heading towards quantification of particular charge stored within base and collector of power BJT and identification of operating modes boundaries. Knowing the excess charge will allow the identification of particular operating stages boundaries during transistor switching process and further generalisation of gained observation to the IGBT switching modeling and analysis.

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