same as that of Is, Nf and Nr extraction. Firstly, according to the expression iB given in Eq.1, some conditions (vBE around 0.7V and BC junction in reverse bias) are proposed to simplify the computation. Because BC junction in reverse bias, all exponential terms with vBC can be ignored. Practical experience shows that the Is and Ise are nA level parameters, which are ignorable before iB. Similarly, in order to improve the accuracy, vBE equals to 0.7V indicates that the vBE/Var can't be ignored compared with 1. In this case, the final base current iB can be written as:

$$i_B = \frac{1}{BF} * \frac{i_C}{\left(1 - \frac{vBE}{V_{AR}}\right)} + Ise * exp\left[\frac{vBE}{NE * vt}\right] \tag{9}$$

The extraction of these parameters needs to use the recursive method. Before applying this method, one additional term E_{rel} will be added into Eq.9 representing the error between theoretical value and measurement.

$$E_{rel_i} = \frac{1}{BF * i_{B_i}} * \frac{i_{C_i}}{\left(1 - \frac{vBE_i}{V_{AR}}\right)} + \frac{Ise}{i_{B_i}} * exp\left[\frac{vBE_i}{NE * vt}\right] - 1 \tag{10}$$

With Eq.10, a new specific function called 'cost function' is proposed as below. 'cost function' is a function that expresses the error between model theory value and actual measurement data. If the 'cost function' gets 0, it means that the model matches perfectly with the measurement.

$$E_{tot} = \sum_{i=1}^{N}\left[\frac{1}{BF * i_{B_i}} * \frac{i_{C_i}}{\left(1 - \frac{vBE_i}{V_{AR}}\right)} + \frac{Ise}{i_{B_i}} * exp\left[\frac{vBE_i}{NE * vt}\right] - 1\right]^2 \quad to\ be\ Minimun \tag{11}$$

Assuming that:

$$i'_{C_i} = \frac{i_{C_i}}{\left(1 - \frac{vBE_i}{V_{AR}}\right)} \tag{12}$$

One calculates the partial derivation of Eq.11 versus Bf and Ise. With the getting derivation results, after simplifications, the Ise can be deduced as follow:

$$Ise = \frac{\sum_{i=1}^{N}\frac{1}{i_{B_i}} exp\left[\frac{vBE_i}{NE * vt}\right] * \sum_{i=1}^{N}\frac{{i'_{C_i}}^2}{{i_{B_i}}^2} - \sum_{i=1}^{N}\frac{i'_{C_i}}{i_{B_i}} * \sum_{i=1}^{N}\frac{i'_{C_i}}{{i_{B_i}}^2} exp\left[\frac{vBE_i}{NE * vt}\right]}{\sum_{i=1}^{N}\frac{1}{{i_{B_i}}^2} exp\left[\frac{2vBE_i}{NE * vt}\right] * \sum_{i=1}^{N}\frac{{i'_{C_i}}^2}{{i_{B_i}}^2} - \left[\sum_{i=1}^{N}\frac{i'_{C_i}}{{i_{B_i}}^2} exp\left[\frac{vBE_i}{NE * vt}\right]\right]^2} \tag{13}$$

Similarly, the Bf can be separated to obtain its expression as:

$$BF = \frac{\sum_{i=1}^{N}\frac{{i'_{C_i}}^2}{{i_{B_i}}^2}}{\sum_{i=1}^{N}\frac{i'_{C_i}}{i_{B_i}} - Ise * \sum_{i=1}^{N}\frac{i'_{C_i}}{{i_{B_i}}^2} exp\left[\frac{vBE_i}{NE * vt}\right]} \tag{14}$$

Now it can be observed that only Ne remains unknown in Eq.11. Therefore, a starting value of the Ne will be selected and will be substituted into the Bf and Ise expression. Then, the three parameters (Bf, Ise and Ne) will be substituted together into Eq.11 to compute the value of 'cost function'. One Repeats the above steps and constantly changes the value of Ne until making the 'cost function' the minimum, which means that the theoretical model is the closest to the actual measurements. The average value is calculated as the final model parameter:

Tab-6: extraction results of Ne, Ise and Bf

	Chip-1	Chip-2	Chip-3	Average
Ne	1.967	1.973	1.972	1.971
Ise(A)	1.29E-9	1.33E-9	1.30E-9	1.30E-9
Bf	325	326	323	325

The reverse parameters extraction method is totally the same as that of forward parameters, just be attention at using the curve iB-vBC instead of the iB-vBE. After computation, the extraction result is as follow:

Tab-7: extraction results of Nc, Isc and Br

Nc	Isc (A)	Br
1.48	1.36E-9	45

C.3. Extraction of Ikf and Ikr

These parameters present the current roll-off phenomenon when it is high. The extraction of Ikf will use all the parameters that have been extracted previously. So, its extraction process must be very careful to ensure its value in a reasonable range as well as to ensure the success of simulation. The extraction of Ikf needs two groups of measured data: iC-vBE and iB-vBE; the measuring configuration is the same as that used in Is, Nf and Nr extraction.

To simplify the extraction, some conditions (vBE around 0.7v and BC junction in reverse bias) should be respected. The amplification expression of a transistor h_{FE} equals to the ratio of iC and iB, which are replaced by their respective mathematic equations to obtain a new amplification expression:

$$h_{FE} = \frac{i_C}{i_B} = \frac{1 - \frac{vBE}{V_{AR}} - \frac{vBC}{V_{AF}} - \frac{i_C}{I_{KF}}}{\frac{1}{BF} + \frac{Ise}{Is} * exp\left[\frac{vBE}{vt}\left(\frac{1}{NE} - \frac{1}{NF}\right)\right]} \tag{15}$$

In Eq.15, only parameter Ikf is unknown. The same method used in the extraction of Ne, Ise and Bf will be employed again here to identify the value of Ikf. According to the expression of h_{FE} , a new 'cost function' is constructed:

$$E_{tot} = \sum_{i=1}^{N}\left[\frac{i_{B_i}}{i_{C_i}} * \frac{1 - \frac{vBE_i}{V_{AR}} - \frac{vBC_i}{V_{AF}} - \frac{i_{C_i}}{I_{KF}}}{\frac{1}{BF} + \frac{Ise}{Is} * exp\left[\frac{vBE_i}{vt}\left(\frac{1}{NE} - \frac{1}{NF}\right)\right]} - 1\right]^2 \rightarrow to\ be\ Minimun \tag{16}$$

The extraction principle is to continuously iterate the new Ikf and to calculate the value of 'cost function' after each iteration until getting its minimum. At this moment, the Ikf gets its optimal value and it also means that the model parameters best meet the actual measurements. The parameter Ikf begins to influence the collector current iC when its value exceeds a certain intensity. Based on this principle and aimed to make the extraction more reasonable, this article selects the data segment of vBE≥0.7V to ensure the collector current iC working under high intensity.

As shown in Fig.7, after certain iterations, the 'cost function' gets its minimum when the Ikf equals to 13A.