Silicon Controlled Rectifier (SCR)

Lecture – 11

TDC PART – I
Paper - II (Group - B)
Chapter - 5

by:

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V-I Characteristics of SCR

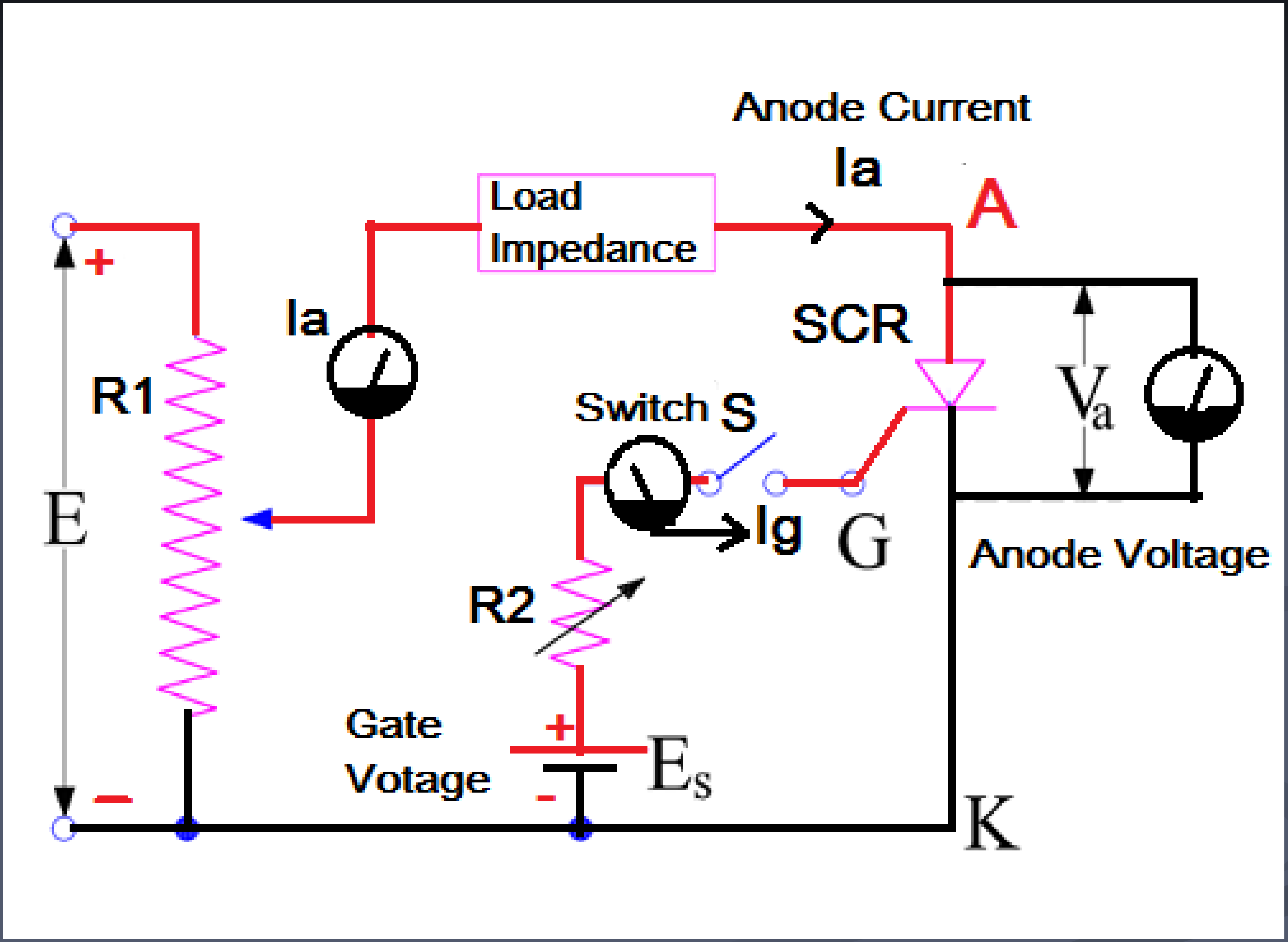
- A **SCR or thyristor** is a **Four Layer, 3 junction, P-N-P-N Semiconductor Device** consisting of at least **three P-N Junctions,** functioning as an **electrical switch** for **high power operations.** It has **three basic terminals,** namely the **Anode (A), Cathode (K)** and the **Gate (G)** mounted on the semiconductor layers of the SCR device.

Definition of V-I Characteristics of SCR

- A **V-I Characteristic** of **SCR (Silicon Controlled Rectifier)** is the **Voltage Current Characteristics.** The current through the SCR varies as the **Anode (A) to Cathode (K) terminal** voltage and **Gate (G) to Cathode (K) terminal** voltage is varied. **The Graphical Representation of Current flowing through the SCR and Voltage across the Anode (A) to Cathode (K) terminal is known as V-I Characteristics of SCR.**

Circuit Diagram for Obtaining V-I Characteristics of SCR

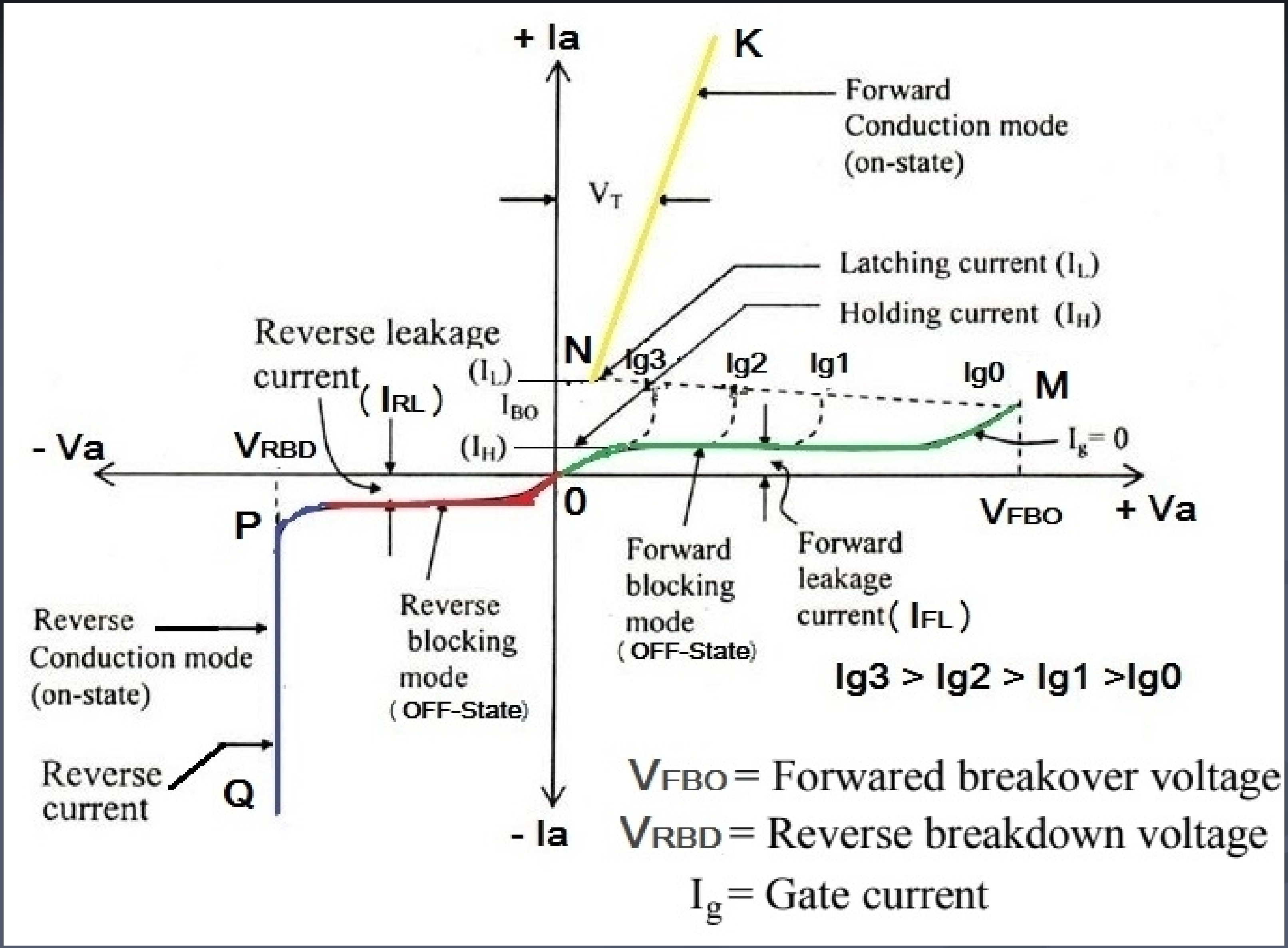
- To obtain **V-I characteristics of SCR,** its **Anode (A)** and **Cathode (K)** are **connected** to the **Supply Voltage source (E) through the load.** The **Gate (G)** and **Cathode (K)** are fed through a **separate Supply Voltage source (Es)** which is meant to provide **Positive Gate Current** from **Gate (G) to Cathode (K)** terminal. The elementary circuit diagram for determining or obtaining **V-I characteristics of SCR (thyristor)** is shown in the **Figure (44)** below.



- **Fig (44)** Shown the Elementary Circuit Diagram for determining V-I characteristics of SCR (thyristor).

- From the above diagram, we can see the **Anode** and **Cathode** terminals **A & K** are connected to **main Variable Supply Voltage Source E** through **Load.** Another **Secondary Supply Voltage Source Es** is applied between the **Gate (G)** and the **Cathode (K)** terminal which supplies for the **Positive Gate Current (Ig = +ve)** when the **Switch S is closed.** From **Fig (44),** we can see that an **Ammeter** connected in series between **Main Supply Voltage Source (E) and Anode (A) terminal of SCR** for **measure Anode Current (Ia).** Similarly another **mill-ammeter** connected in **Series** between **Secondary Supply Voltage Source (Es) and Gate terminal of SCR** for **measure Gate Current (Ig).** A **Voltmeter** also connected **across Anode (A) and Cathode (K) terminal of SCR** in **Parallel mode** for measure **Anode Voltage (Va).**

- The **Variable Resistor R1** supply **Main Variable Voltage (E)** between **Anode (A) and Cathode (K)** terminals of SCR. Similarly Variable Resistor R2 supply **Secondary Variable Voltage (Es)** for the **Gate** terminal voltage of SCR. On giving the supply we get the required **V-I characteristics** of a **SCR (thyristor)** shown in the **Figure (45) below** for **Anode to Cathode Voltage (Va)** and **Anode Current (Ia)** as we can see from the circuit diagram. **Va and Ia represents** the **Voltage** across the **Anode (A) to Cathode (K) terminals** and **Anode Current through the SCR.** A plot between **Anode Voltage (Va)** and **Anode Current (Ia)** is drawn by varying the **Source Voltage E** and noting the corresponding **Current** through SCR. **This plot gives the V-I characteristics of SCR.** A typical V-I Characteristics of SCR is shown in **Fig (45)** below.



- **Fig (45)** Shown a Typical V-I Characteristics of SCR.

Various Modes in V-I Characteristics of SCR

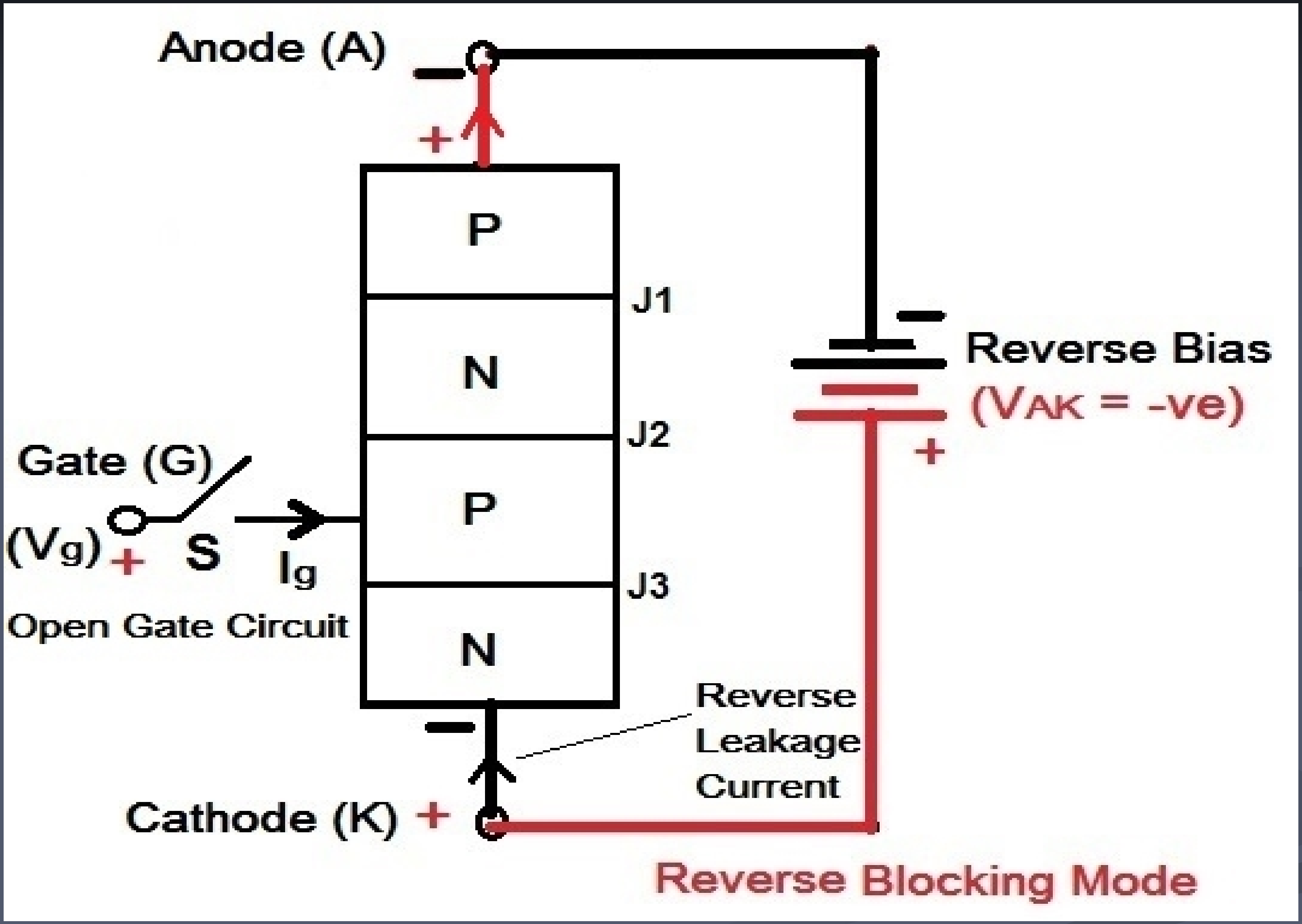
- A careful observation and detailed study of the **V-I characteristics** reveal that the **SCR (thyristor)** has **three basic mode of operation** namely the,

- **(1) Reverse Blocking Mode (OFF-State),**
- **(2) Forward Blocking Mode (OFF-State), and**
- **(3) Forward Conduction Mode (ON-State)**

- The above **basic modes of operations** are discussed in great details below, to **understand the overall characteristics of a SCR (thyristor).** Let us now discuss each of the **three modes** one by one.

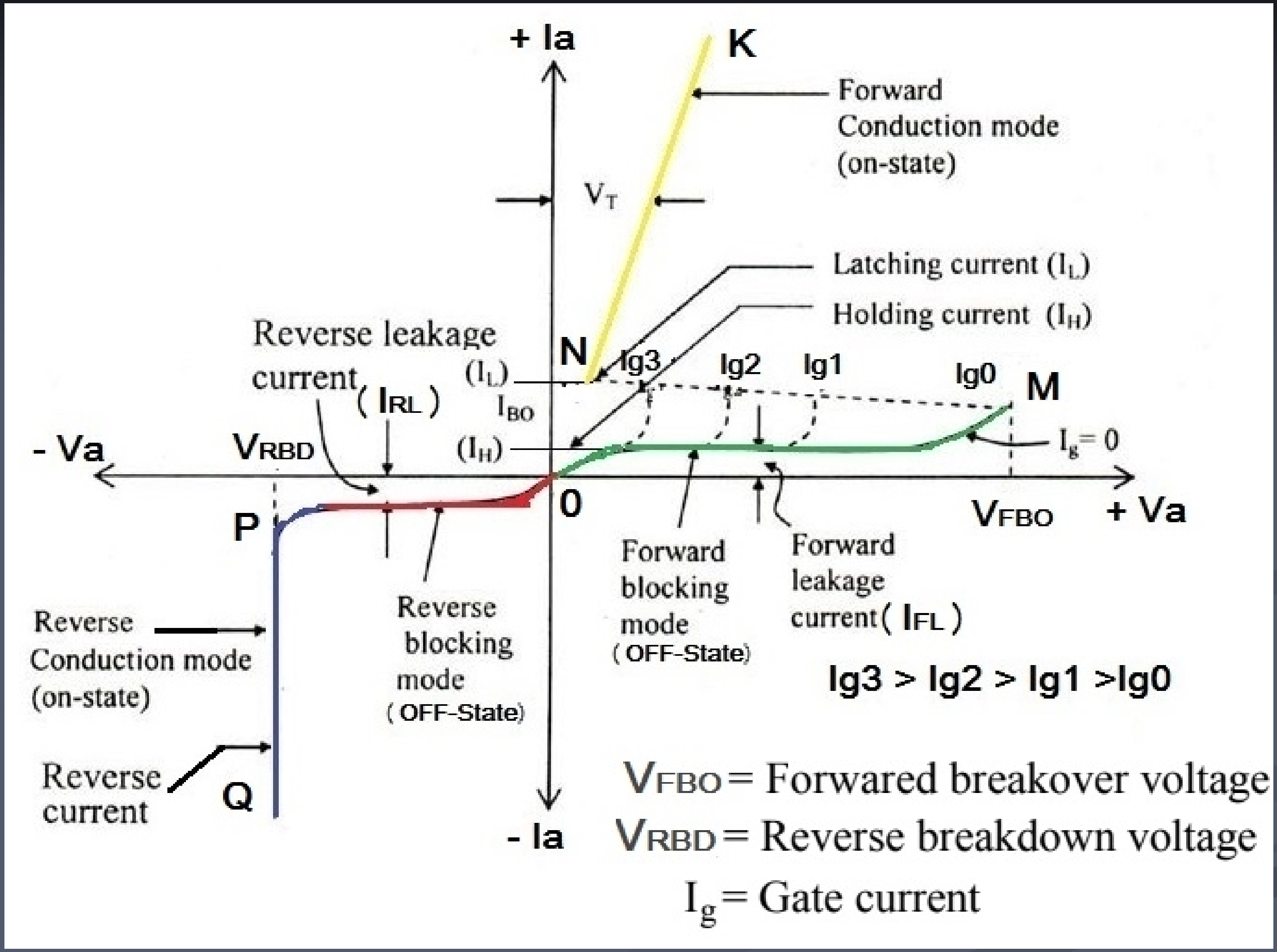
(1) Reverse Blocking Mode (OFF-State)

- Initially for the **Reverse Blocking Mode** of the **SCR**, the **Cathode (K)** is made **Positive (+)** with respect to **Anode (A)** by supplying **Voltage E** and the **Gate (G) to Cathode (K) Supply Voltage Es** is detached initially by keeping **Switch S open. Reverse Blocking Mode Circuit Arrangement of the SCR** is shown in **Fig (46).** For **understanding this mode** we should look into the **Third Quadrant of V-I characteristics of SCR** where the **SCR is Reverse Biased.**



- **Fig (46) Shown** Reverse Blocking Mode (OFF-State) Circuit Arrangement of the SCR.

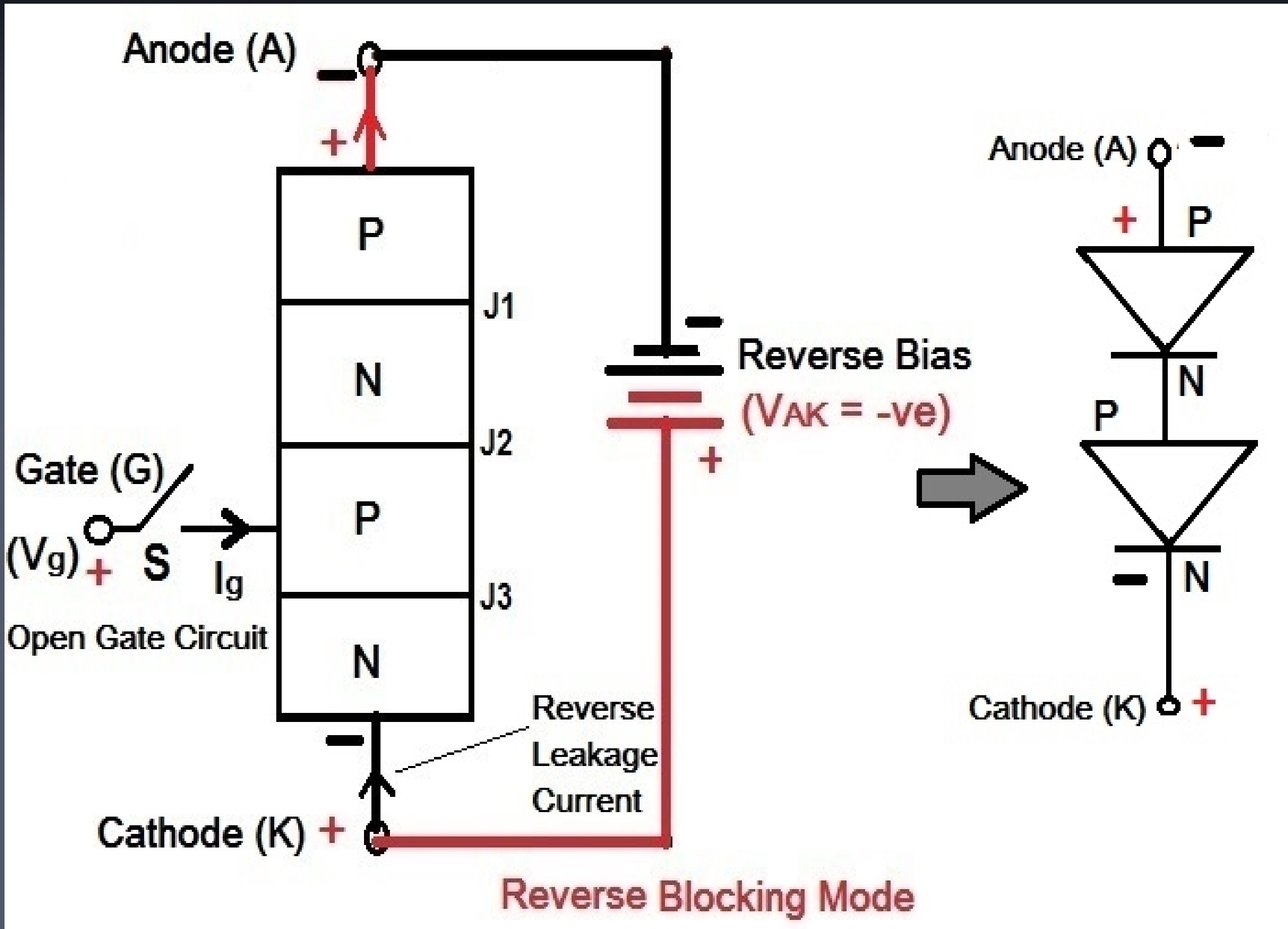
- **Reverse Blocking Mode of SCR** is that operational mode in which it offers **High Impedance for current flow** and hence do **not conduct.** An **SCR** in **Reverse Blocking Mode** behaves as an **Open Switch or OFF-Switch.** Hence **this mode** is also known as **OFF-State of SCR.** It is shown by **RED Colour Curve O-P** in the **V-I characteristics of SCR** shown in **Fig (47)** below.



- **Fig (47)** Shown a Typical V-I characteristics of SCR.

- As clear from the **V-I characteristics curve** shown in **Fig (47)** above, the **Anode (A) to Cathode (K) Voltage in is Negative (-) in this mode.** This means that **Anode (A)** terminal is **made Negative with respect** to **Cathode (K)** with **Switch S Open**. This leads to **Reverse Biasing** of the **SCR**. Here consequently **Junctions J1 and J3** are **reverse biased** whereas the **junction J2** is **forward biased**.

- The **behavior of the SCR (thyristor)** here is **similar to that of two diodes** are **connected in series** with **Reverse Voltage applied across them;** shown in **Fig (48).** As a result only a small **Reverse Leakage Current (IRL) also known as a Reverse Saturation Current,** of the order of **few mili ampere (mA) or micro ampere (μA) flows** thorough the SCR in this mode. This is the **Reverse Blocking Mode** or the **OFF-State,** of the **SCR (thyristor).**



- **Fig (48)** Shown SCR similar to that of two diodes are connected in series with Reverse bias Voltage applied across them.

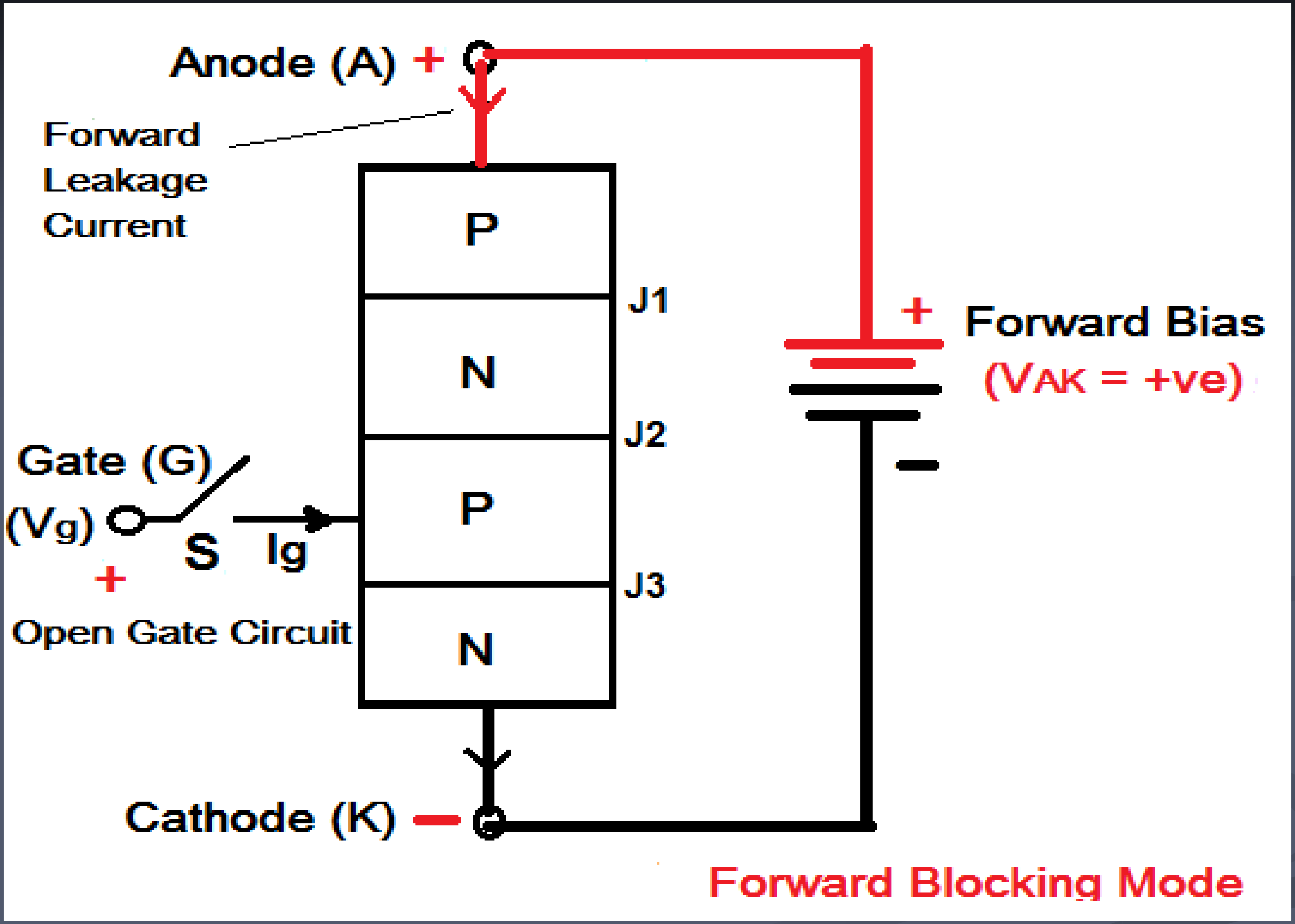
- If the **Reverse Bias Voltage** is now **increased,** then at a particular voltage, known as the critical **Reverse Voltage VRBD,** an **Avalanche Breakdown** takes place at **Reverse Biased junctions J1 and J3** which leads to **sudden increase** in **Reverse Current.** This critical **Reverse Voltage** is **called Reverse Breakdown Voltage (VRBD) . VRBD** represents this **Reverse Breakdown Voltage** in the **V-I characteristics of the SCR**. It can be seen that, there is a **sharp increase** in **Reverse Current** at this voltage. This **increased large current** associated with **Reverse Breakdown Voltage VRBD** may gives **rise to more losses** in the **SCR**, **which results in heating.**

- This may **lead to thyristor damage** as the **junction temperature may exceed its permissible temperature rise.** It should, therefore, be ensured that maximum working **Reverse Voltage** across SCR (thyristor) terminals should not exceed **Reverse Breakdown Voltage V_{RBD}** during its operation.

- When reverse voltage applied across a thyristor is less than **Reverse Breakdown Voltage V_{RBD}**, the **SCR** (thyristor) **device** offers **very High Impedance in the reverse direction** and **hence do not conduct.** This is the reason; the **SCR** in the **Reverse Blocking Mode** may therefore be treated as **Open Circuit**.

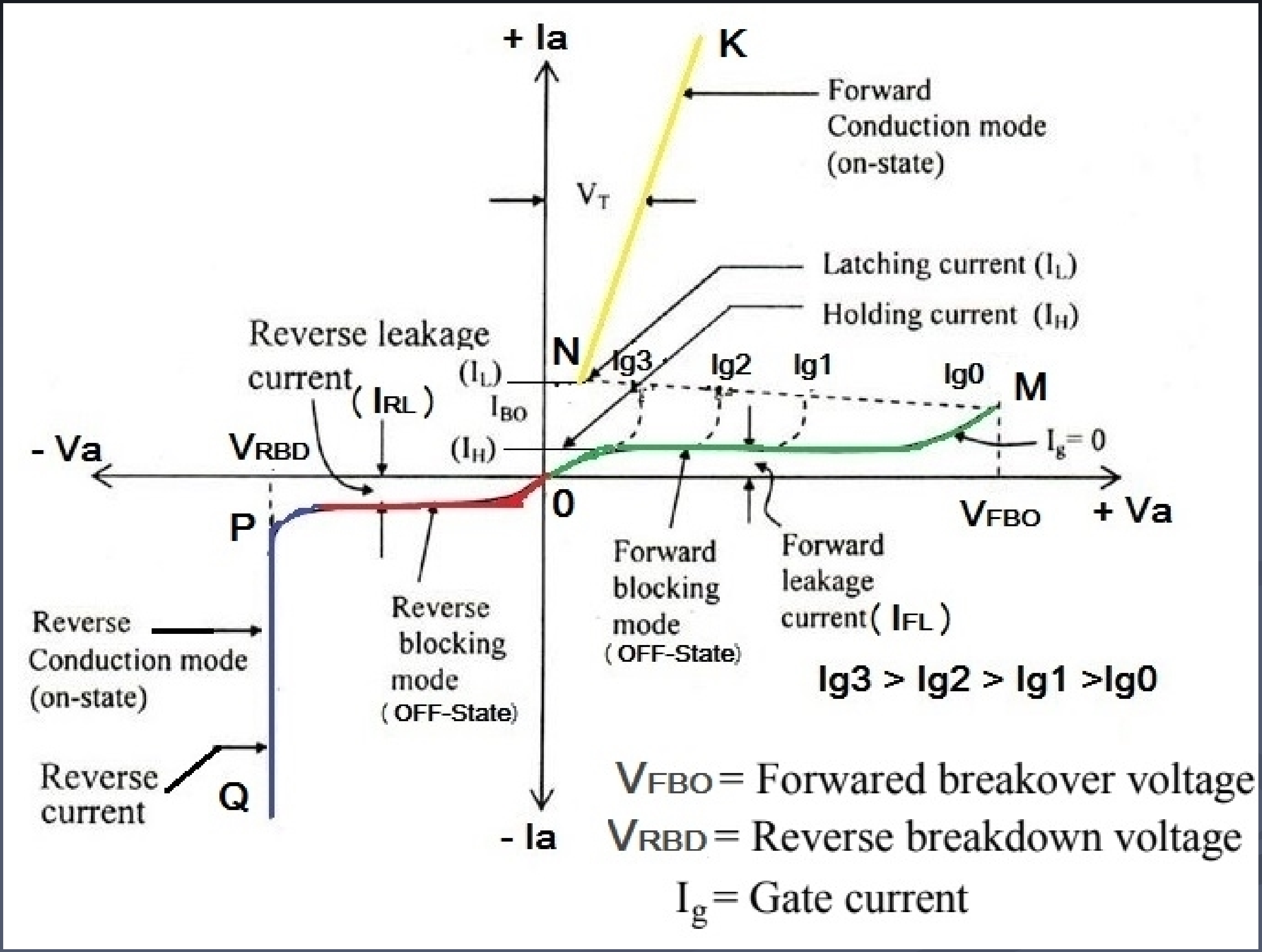
(2) Forward Blocking Mode (OFF-State)

- Initially for the **Forward Blocking Mode** of the SCR (thyristor), the **Anode (A) is Positive (+)** with respect to the **Cathode (K),** by **Supplying Voltage E** and the **Gate (G) to Cathode (K) Supply Voltage Es** is detached initially by keeping **Switch S open (OFF-Switch)** to kept **Gate (G)** terminal in **Open condition.** The SCR (thyristor) is now said to be **Forward Biased** as shown the **Figure (49)** below. For understanding this mode we should look into the **First Quadrant of V-I characteristics curve of SCR** where the SCR (thyristor) is **Forward Biased Condition.**



- **Fig (49)** Shown Forward Blocking Mode Circuit (OFF-State) Arrangement of the SCR.

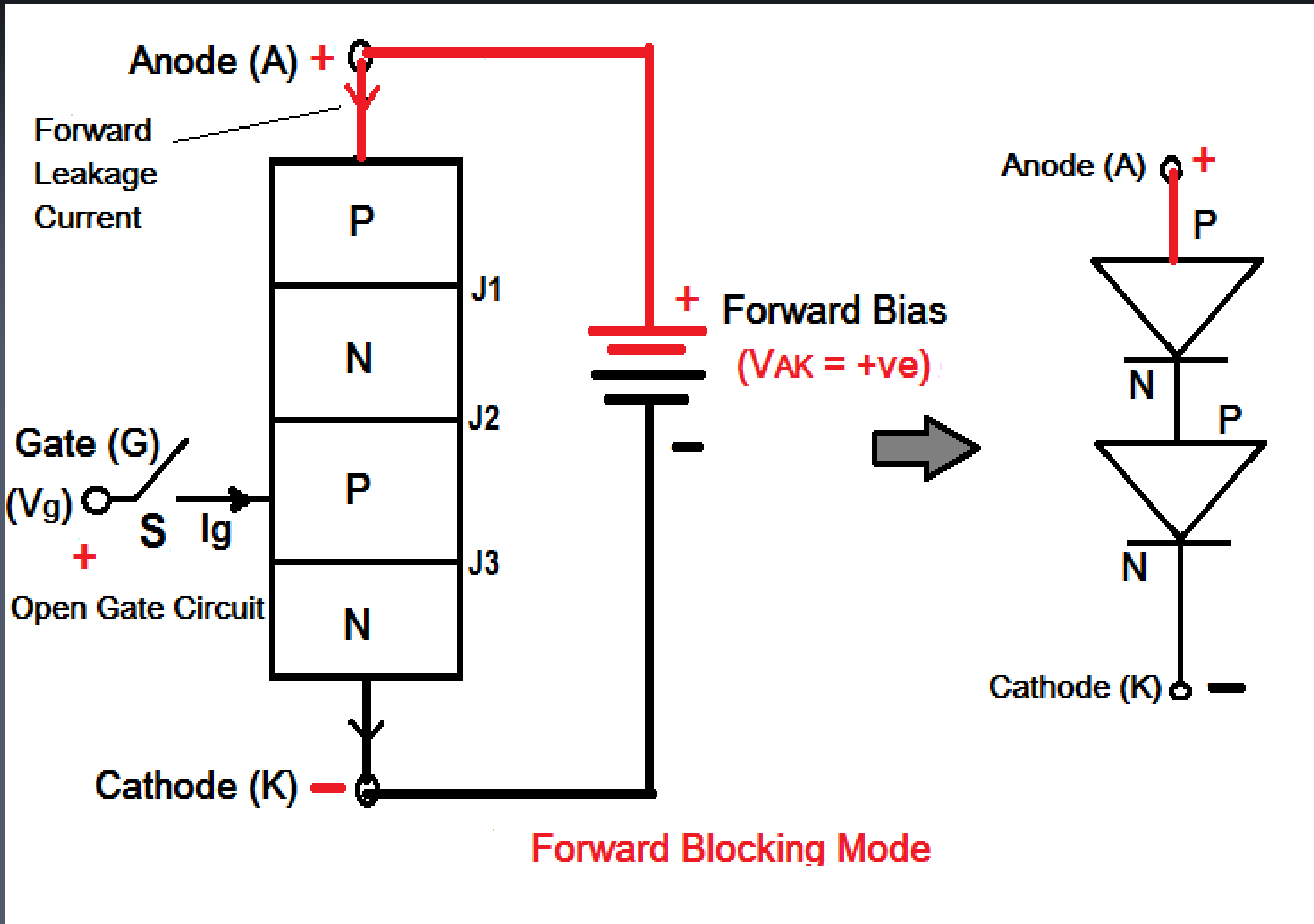
- **Forward Blocking Mode of SCR** is that **operational mode** in which **it offers High Impedance for current flow** and hence do not conduct. An SCR in **Reverse Blocking Mode** behaves as if an **Open Switch or OFF-Switch.** Hence **this mode** is also known as **OFF-State of SCR.** It is shown by **Green Colour Curve O-M** in **the V-I characteristics of SCR** shown in **Fig (50**) below.



- **Fig (50)** Shown a Typical V-I characteristics of SCR.

- As clear from the V-I **characteristics curve of SCR**, the **Anode (A) to Cathode (K) Voltage in is Positive (+) in this mode**. This means that **Anode (A) terminal** is made **Positive** with respect to **Cathode (K)** with **Switch S Open.** This leads to **Forward Biasing of the SCR.** Here consequently **Junctions J1 and J3** are **Forward Biased** whereas the **junction J2** is **Reverse Biased** applies across them.

- The **behavior of the SCR (thyristor)** here is **similar to that of two diodes** are **connected in series** with **Forward Voltage applied across them;** shown in **Fig (51).** As a results only a small **Forward Leakage Current (I_{FL}),** of the order of **few mili ampere (mA) flows** thorough the SCR in this mode. This is the **Forward Blocking Mode** or the **OFF-State,** of the **SCR (thyristor).**



- **Fig (51)** Shown SCR similar to that of two diodes are connected in series with Forward Bias Voltage applied across them.

- As we can see from **Fig(49)** the **junctions J1 and J3** are now **Forward Biased** but **junction J2** goes into **Reverse Biased condition**. In this particular mode, a **Small Leakage Current,** called **Forward Leakage Current (I_{FL})** is allowed to flow initially as shown by **Green Colour Curve O-M** in the **V-I characteristics curve of SCR (thyristor).** As the **Forward Leakage Current (I_{FL})** is **small, SCR offers High Impedance.** Therefore an SCR can be treated as an **Open Switch or OFF-Switch even in Forward Blocking Mode.**

- If the **Forward Voltage** is now **increased** and **Gate Voltage (Vg)** is **keep constant** then at a particular voltage, known as the **Critical Forward Voltage V_{FBO}**, an **Avalanche Breakdown** takes place at **Forward Biased junctions J2 which leads to sudden increase in Forward Current** also called **Anode Current (Ia)** in **Forward Direction** in this **Forward Blocking Mode.** This **critical Forward Voltage** is called **Forward Breakover Voltage V_{FBO}.**
  V_{FBO} represents this **Forward Breakdown Voltage** at **Point M** in the **V-I characteristics** of the SCR as shown in **Fig (50).** It can be seen that, there is a **sharp increase** in **Forward Current (Anode current Ia)** in **forward direction** at this voltage.

- Now, if we **keep on increasing** the **Forward Biased Anode (A) to Cathode (K) Voltage** then in this particular mode, the SCR (thyristor) conducts **Very Large Forward Currents** from **Anode (A) to Cathode (K)** with a **very small voltage drop across it.** A **SCR (thyristor) is brought from Forward Blocking Mode (OFF-State) to Forward Conduction Mode (ON-State)** by **Turning it ON** by **increasing** the **Forward Biased Anode (A) to Cathode (K) Voltage** that **exceeding the Forward Breakover Voltage (V_{FBO}) higher or by applying a Positive (+) Gate Pulse** between **Gate (G) and Cathode (K).** In this mode, **SCR (thyristor)** is in **ON-State** and behaves like a **Closed Switch or ON-Switch.**

- **Voltage drop across SCR (thyristor)** in the **ON-State** is of the order of **1 V to 2 V** depending beyond a certain point, and then the **Reverse Biased junction J2** will have an **Avalanche Breakdown** at a voltage called **Forward Breakover Voltage (V_{FBO})** of the SCR (thyristor). But, if we keep the **Forward Voltage** applied across a SCR (thyristor) is **less than Forward Breakover Voltage (VFBO**), as we can see from the V-I characteristics of SCR (thyristor) **shown in Fig (50),** the SCR device offers **High Impedance** in the **Reverse Direction and hence do not conduct.** This is the reason; the SCR (thyristor) in the **Forward Blocking Mode (OFF-State)** may therefore be **treated as Open Circuit or Turn-OFF.**

(3) Forward Conduction Mode (ON-State)

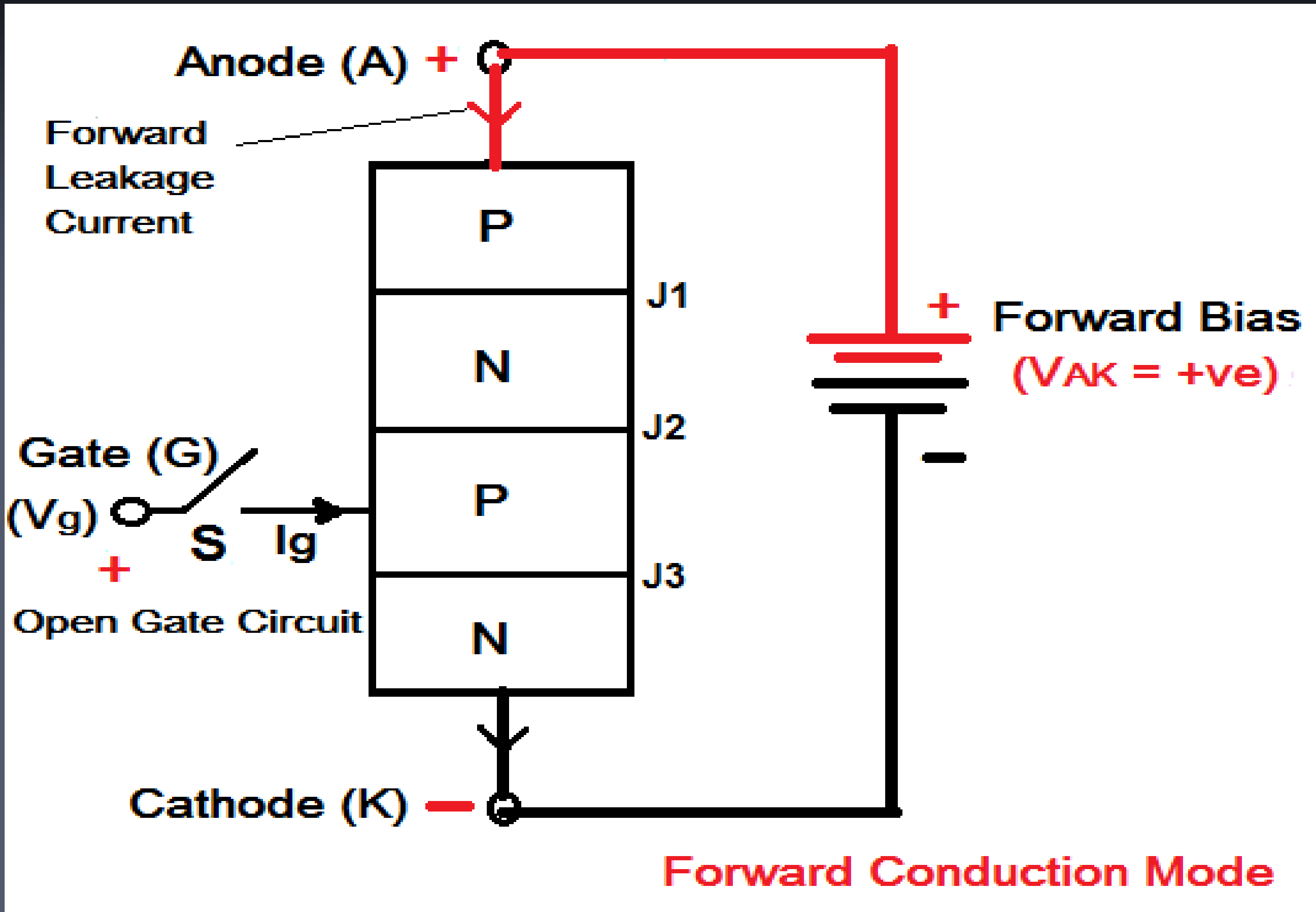
- As we have seen that in **Forward Blocking Mode,** even through the **SCR** is **Forward Biased,** it does not conduct. But the good thing is that, in **Forward Blocking Mode**, **junction J1 and J3** are forward biased and **junction J2** is reversed biased. This means, there are **two possibilities** for making **SCR** to conduct in this **Forward Blocking Mode** :-

- **(1) <u>In the First Case :-</u> Increase the anode to cathode voltage to such an extent which leads to Avalanche Breakdown of the reverse biased junction J2.**

- **(2) <u>In the Second Case :-</u> Apply positive gate pulse between gate and cathode terminal also called Gate Triggring.**

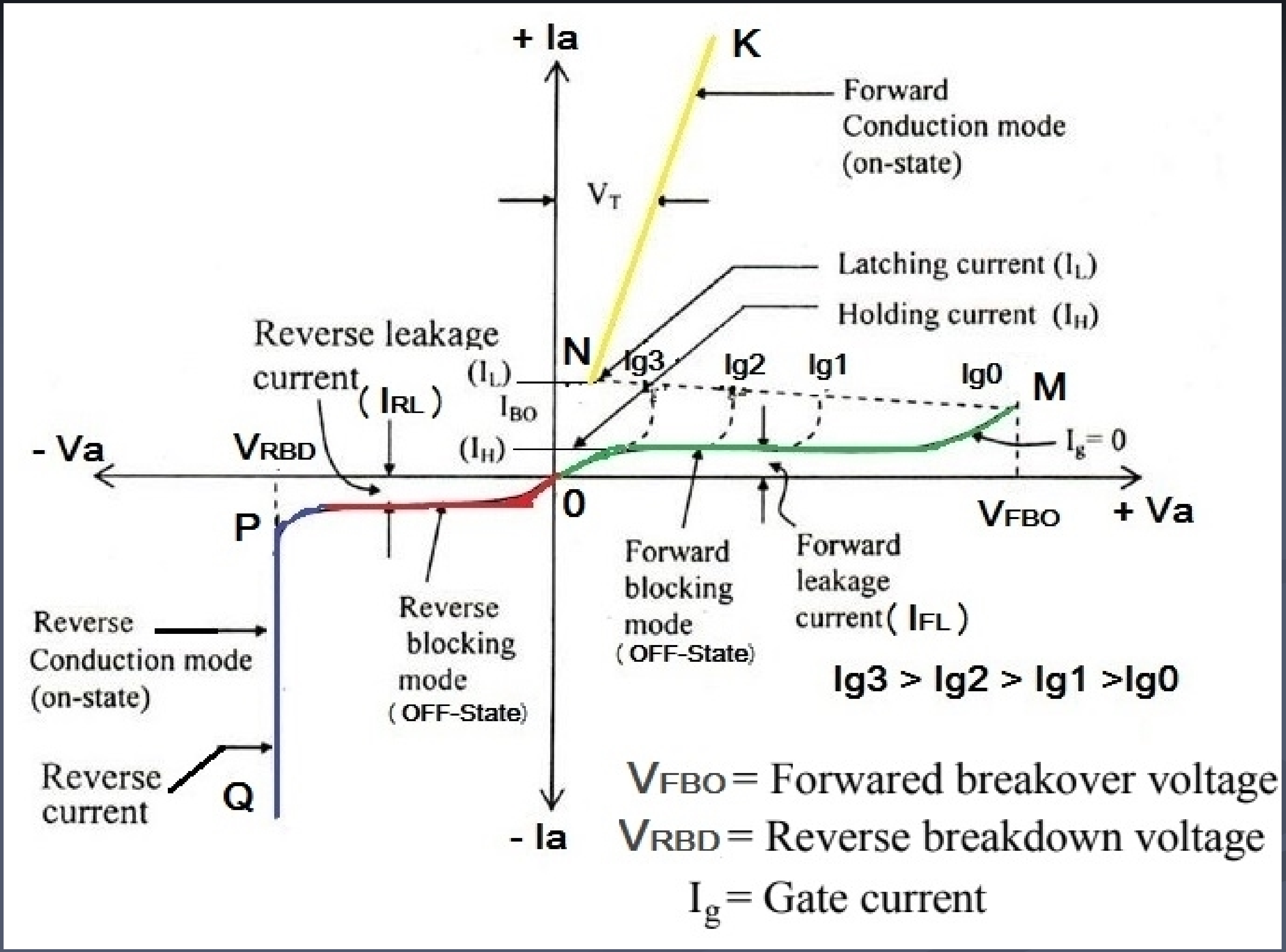
- **Carefully Noted here that** Once any one of these methods is applied, the **Avalanche Breakdown** must be occurs at **junction J2**. Therefore the **SCR** turns into **Forward Conduction Mode** and acts as a **Closed Switch (ON-State)** thereby **Forward Current** starts flowing through **SCR.**

- **(1) In the First Case :-** Since **Forward Blocking Mode, Junctions J1 and J3** are **Forward biased** whereas the **junction J2** is **Reverse biased** due to **Forward Bias Voltage** applied between **Anode (A) and Cathode (K)** terminal of SCR; as shown in **Fig (52).** When the **Anode (A) to Cathode (K) Forward Biasing Voltage** is increased, with **Gate Circuit Open,** then at some **Critical Voltage V_{FBO}** the **Reverse Biased junction J2** will have an **Avalanche Breakdown** and the **Critical Voltage** at which **Avalanche Breakdown** occurs is known as **Forward Breakover Voltage (V_{FBO})**. As other **junction J1 and J3** are already **Forward Biased**, breakdown of **junction J2** allows **free movement of majority carriers** across all **three junctions J1, J2 and J3** and as a **result in sudden increase in Small Anode Current (Ia) also called as Forward Leakage Current (I_{FL})** to **Very Large Forward Anode Current (Ia)** flows in forward direction leading to **SCR (thyristor) Turn -ON.**



- **Fig (52)** Shown Forward Conduction Mode Circuit (ON-State) Arrangement of the SCR with anode to cathode forward biasing voltage is increased, and gate circuit open.

- This results in the sudden increase in the **Small Forward Leakage Current (Small Anode Current) to Very Large Forward Anode Current (Ia)** flowing through the SCR therefore the SCR turns into **Forward Conduction Mode (ON-State)** and acts as a **Closed Switch (ON-State),** hence device conduct. **This mode is known as Forward Conduction Mode (ON - State).** In **Forward Conduction Mode (ON-State), Very Large Anode Current (Ia)** is limited only by External Load Impedance. When Forward voltage is higher then **Forward Break-Over Voltage (V_{FBO}), SCR offers Very Low Impedance due to Very Large Forward Anode Current though SCR. Very Large Forward Anode Current flow is shown by the Yellow Colour Line N-K in V-I Characteristics of SCR in Figure (53) below,** although the Gate (G) terminal of the SCR is **un-Biased (Open).**



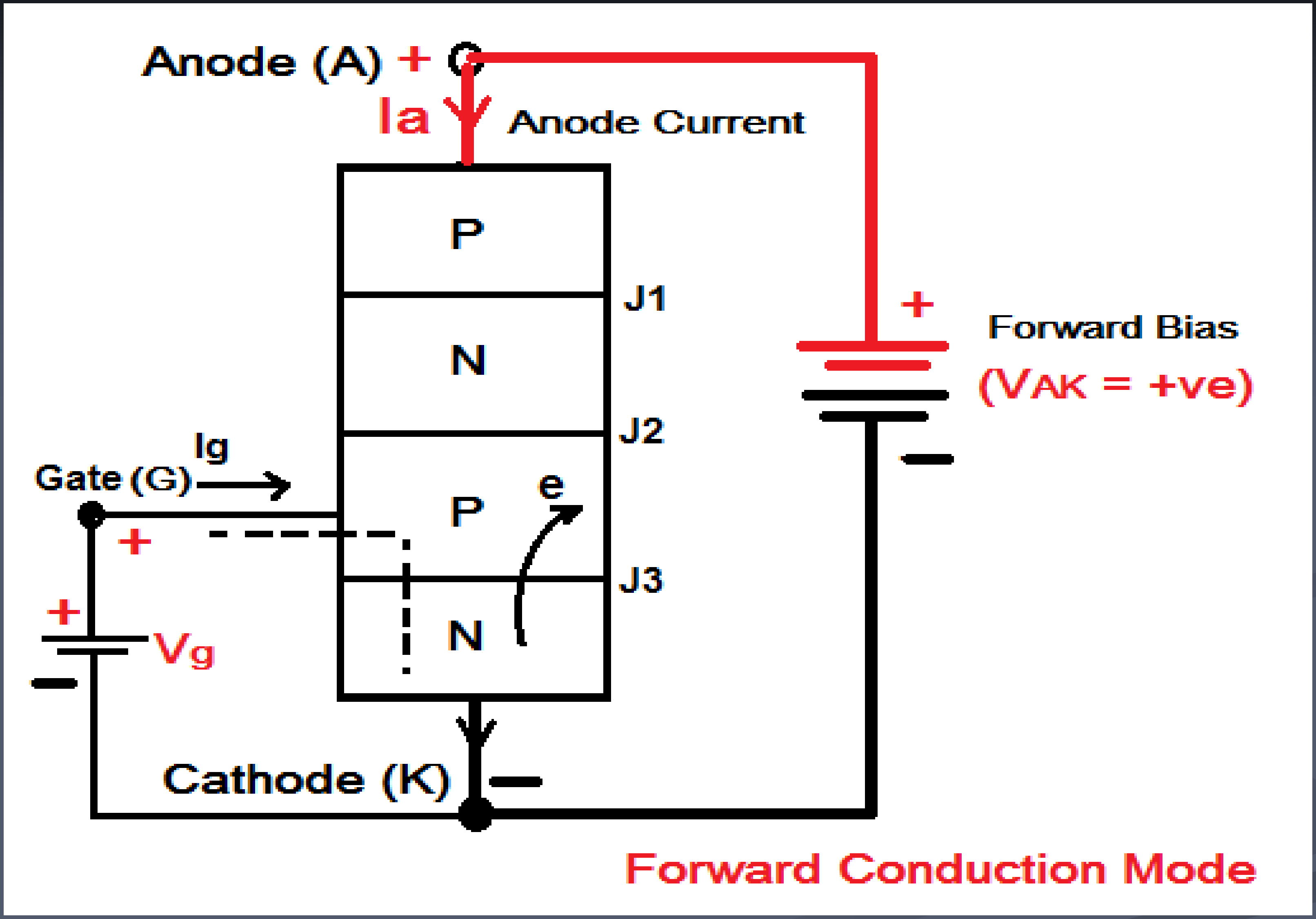
- **Fig (53)** Shown a Typical V-I characteristics of SCR.

- Once the **SCR (thyristor)** is **Turned-ON** we can see from the diagram for **V-I characteristics** of SCR (thyristor) Shown in **Fig (53) and (55)** that the **Point-M** at once shifts toward **Point-N** and then anywhere between **Point-N** and **Point-K**. Why in between **Point -N** and **Point-K**? Since the **Anode Current (Ia)** in this mode will only be limited by the load, so based on the value of load the **Anode Current (Ia)** will change and may lie at any point in between **Point-N** and **Point -K.** Thus **Line N-K** represents the **Forward Conduction Mode of the SCR** (thyristor). In this mode of operation, the thyristor conducts maximum current with minimum voltage drop, this is known as the **Forward Conduction or the Turn-ON Mode** of the SCR (thyristor).

- <u>**(2) In the Second Case :-**</u> Gate triggering is the method in which **Positive Gate Current** is flown in **Forward Biased SCR** to make it ON. **Gate triggering** is in fact the most reliable, simple and efficient way to **Turn-ON SCR. Therefore** it is the most usual method of firing the **Forward Biased SCRs.** A SCR with **Forward Breakover Voltage (V_{FBO})** higher than the normal working voltage is chosen. This means that SCR (thyristor) will remain in **Forward Blocking Mode** with normal working voltage across **Anode (A) and Cathode (K)** and with **Gate (G) terminal Open.**

- However, when **Turn-ON of a SCR** is required a **Positive (+) Gate Voltage** between **Gate (G) and Cathode (K)** is applied with **Gate Current,** thus **charges carriers are injected into the inner P-type layer** and voltage at which **Forward Breakover** occurs is reduced. The Forward Voltage at which the device switches to ON-State depends upon the magnitude of **Gate Current**. Higher the Gate Current, **lower is the Forward Breakover Voltage (V_{FBO}).**

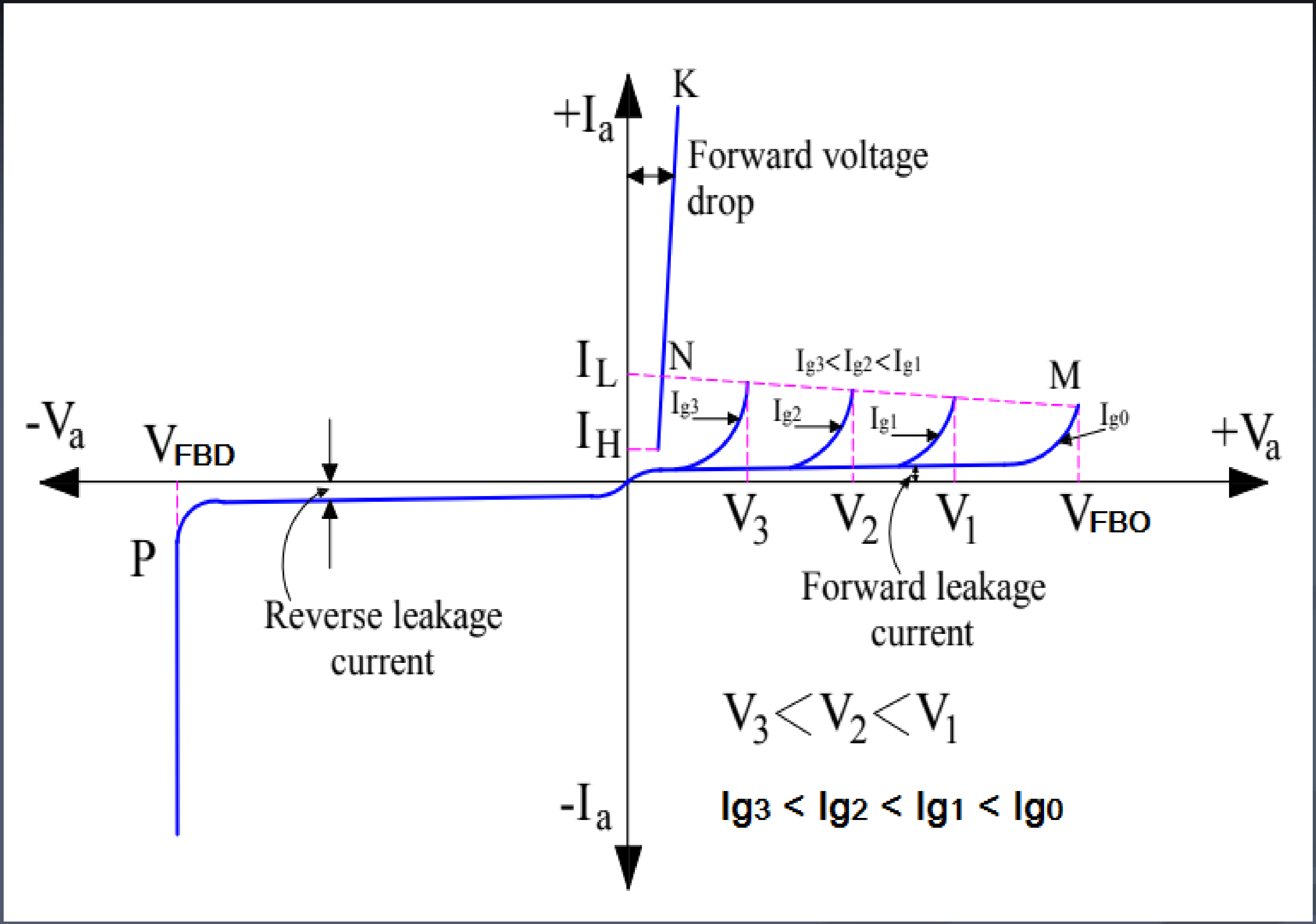
- In this mode, Positive Gate Voltage between Gate (G) and Cathode (K) terminals are applied in Forward Biased SCR which establishes Gate Current from Gate (G) terminal to Cathode (K) as shown in **Fig (54)** below.



- **Fig (54)** Shown Gate Triggering method in which **Positive Gate Current** is flown in **Forward Biased SCR** to make it ON.

- When **Positive Gate Current** is applied, **Gate P-type layer** is flooded with **Electrons** from the **Cathode (N-type side).** This is because the **Cathode N-type layer** is **heavily doped** as compared to **Gate P-type layer.** Since the SCR (thyristor) is Forward Biased then **junction J1 and J3** are also **Forward Biased,** due to this, the injected **Electrons** in **Gate P-type layer** may reach **junction J2.** As a result the width of Depletion Layer around junction J2 is reduced. This result is reduction of **Forward Breakover Voltage (VFBO).** This causes the junction J2 to Breakdown at an applied voltage lower than **Forward Breakover Voltage (VFBO).**

- If the magnitude of Gate Current is increased, **more the injected Electrons** in **Gate P-type layer,** the more will be chance of **Electrons** reaching **junction J2, as a consequence SCR (thyristor)** will get **Turned-ON** at a much lower applied Forward Voltage. This means the more the value of **Gate Current,** the more will be reduction in **Forward Breakover Voltage (V_{FBO}). Thus Gate Current and Forward Breakover Voltage are inversely proportional.** Please refer the **Figure (55) below. Fig (55)** Shown below the **V-I characteristics of a SCR** for different values of **Gate Current Ig.**



- **Fig (55)** Shown the **V-I characteristics of a SCR** for different values of **Gate Current Ig.**

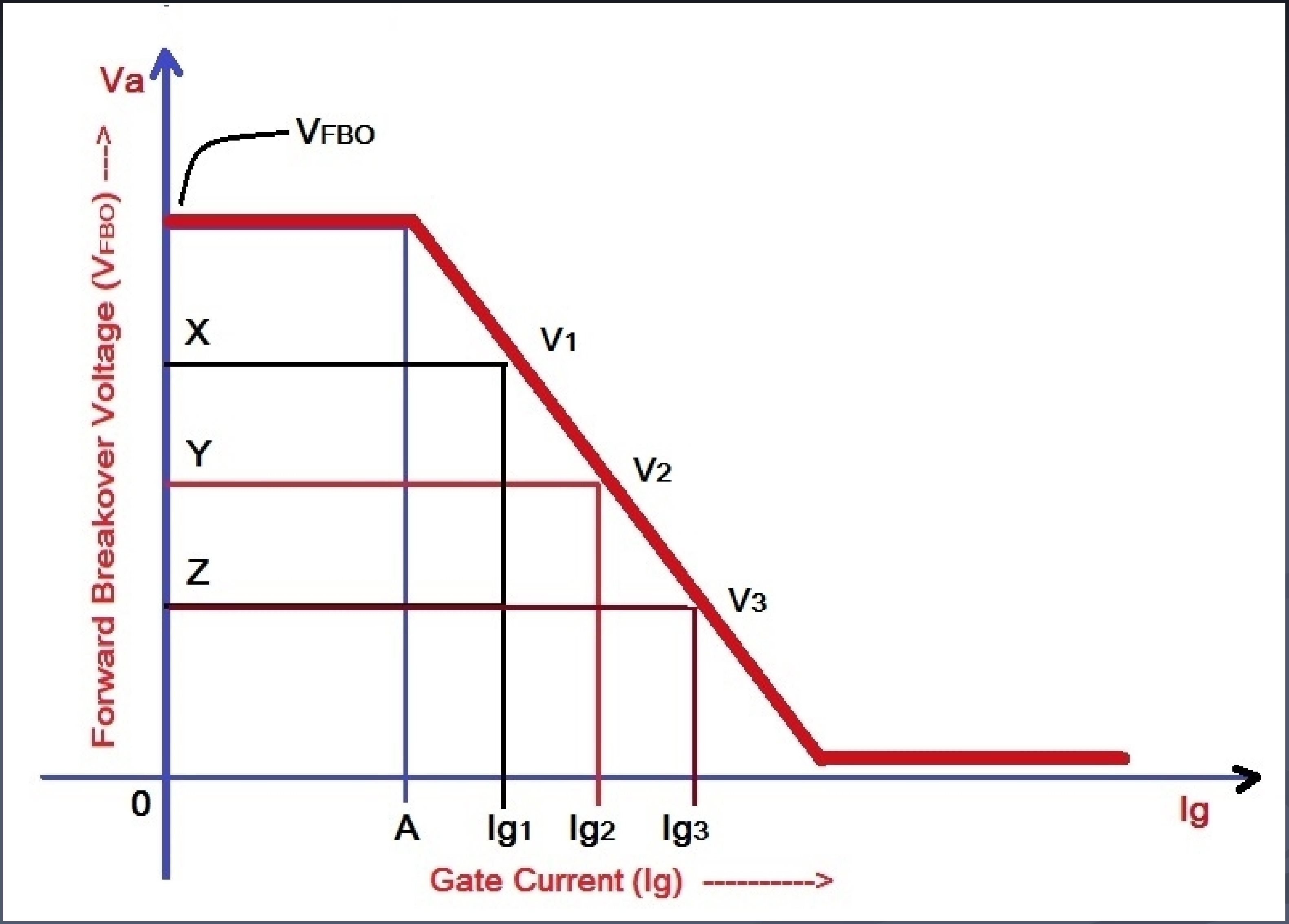
- Following points can be observed and noted from the above **Figure (55) shown the V-I characteristics** curve **of a SCR.**

- **(1)** When **the Gate Current Ig** is **zero**, the **Forward Breakover Voltage is V_{FBO}.**

- **(2)** As **Gate Current increases** from **zero to Ig1,** the **Forward Breakover Voltage reduces** from **V_{FBO} to V1.** Similarly, its value reduces from **V1 to V3** as the **Gate Current** increases from **Ig1 to Ig3. The reason behind this is that** the current which is applied to the **Gate (G) terminal** is high then additional electrons will be inserted into the **J2 junction** & consequences to approach into the conduction position at less applied voltage.

- Thus the **SCR** may be **Turned-ON** by applying **Gate Current.** It should be noted that **SCR** is **Turned-ON** due to **Forward Breakover Voltage (V_{FBO})** though this voltage is reduced considerably due to **Positive Gate Current.**

- The effect of Gate Current on the **Forward Breakover Voltage (V_{FBO}) of a SCR (thyristor)** can also be illustrated by means of a curve as shown in **Fig(56)** below.



- **Fig(56)** Shown variation of **Forward Breakover Voltage (VFBO)** with **Gate Current (Ig).**

- From **Fig (56),** for **Ig < OA**, **Forward Breakover Voltage** remains almost constant at **V_{FBO}.** For **Gate Current Ig1, Ig2 and Ig3,** the values of **Forward Breakdown Voltages** are **OX, OY and OZ,** respectively as shown in **Fig (56).** Again from **Fig (56),** the curve marked **Ig = 0** is actually for **Gate Current less than OA**. In practice, the magnitude of **Gate Current** is more than the minimum Gate Current requires to Turn-ON the SCR (thyristor). Typical **Gate Current** magnitudes are of the order of **20 to 200 mA**.

- Once **SCR Starts Conducting** in **Forward direction**, **reversed bias Junction J2** no **longer exists**. Therefore, no **Gate Current (Ig)** is required for **SCR (thyristor)** to remain in **ON-State.** Therefore if the **Gate Current (Ig)** is removed, the conduction of current from **Anode (A) to Cathode (K)** is not affected. However, if **Gate Current (Ig)** is reduced to zero before the rising of **Anode Current (Ig)** to a specific value called the **Latching Current (IL), the SCR (thyristor) will Turn-OFF again. The Gate Current (Ig)** should therefore be chosen to ensure that **Anode Current (Ia)** rises above the **Latching Current (IL)**. This means we should not make **Gate current OFF** until **Anode Current (Ia)** has crossed **Latching Current (IL)**.

- **Latching Current (I_L) is defined as the minimum value of anode current which must be attained during Turn-ON process of SCR to maintain the conduction even when gate current is removed.**

- Once SCR (thyristor) starts conducting, Gate losses its control. The SCR (thyristor) can now be **Turned-OFF** only if the **Anode current** reaches below a specified value of **Anode current.** This value of **Anode current** below which **SCR gets Turned-OFF** is called **Holding Current (I_H).** As can be seen from the V**-I characteristics of SCR,** the value of **Latching Current (I_L)** is higher than the **Holding Current (I_H).**

- **Holding Current (I_H) is defined as the minimum value of anode current below which it must fall for Turning-OFF the SCR (Thyristor).**

Key Terms Related to V-I Characteristics of SCR

- **(1) Forward and Reverse Blocking Regions** are the regions corresponding to the Open-Circuit condition for the controlled Rectifier which Block the flow of charge (current) from Anode (A) to Cathode (K) terminal of the SCR.

- **(2) Forward and Reverse Conduction Regions** are the regions corresponding to the Closed-Circuit condition for the controlled Rectifier which allow the flow of charge (current) from Anode (A) to Cathode (K) terminal of the SCR.

- **(3) Forward Breakover Voltage (V_{FBO})** is that voltage above which the SCR enter the Conduction Region.

- **(4) Reverse Breakdown Voltage (V_{RBD})** is equivalent to the **Zener** or **Avalanche Region** of the fundamental two-layer semiconductor diode that voltage above which the SCR enter the Conduction Region.

- **(5) Latching Current (I_L)** is defined as the minimum value of anode current which must be attained during Turn-ON process of SCR to maintain the conduction even when gate current is removed.

- **(6) Holding Current (I_H)** is defined as the minimum value of anode current below which it must fall for Turning-OFF the SCR (Thyristor).

to be continued ....