Deterministic Theory of the Tunnel Effect in the Esaki Junction

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Abstract

In scientific literature the Esaki junction is considered a typical system of quantum physics and its behavior is explained with the theory of probability. In this article we prove that the functioning of the Esaki junction can be explained very well without making use of the theory of probability but only by means of deterministic physical reasonings. This research is the first step in order to show that it is possible to think on a theory of quantum physics which is able to leave probability aside for a complete and exhaustive understanding of physical phenomena which happen in the microphysical world.

1. The Esaki junction

The Esaki junction is the heart of a solid-state special electronic component (tunnel diode) in which both the P (Positive) zone and the N (Negative) zone are characterized by high levels of doping. It allows to obtain experimentally a very different current-voltage characteristic (fig.1) with respect to that one of a diode with normal levels of doping.
The physical phenomenon that explains the I_p anomalous peak of current in the graph is called " tunnel effect ". It is interpreted by reasonings of quantum mechanics which accepts, unlike classical physics, that a particle with energy E has a non-null finite probability to exceed a barrier of potential energy $E_p>E$. That probability is inverse to the length of the zone of barrier for which the tunnel effect is the more strong the more the length of the zone of barrier is small and on this account the more the level of doping is high.

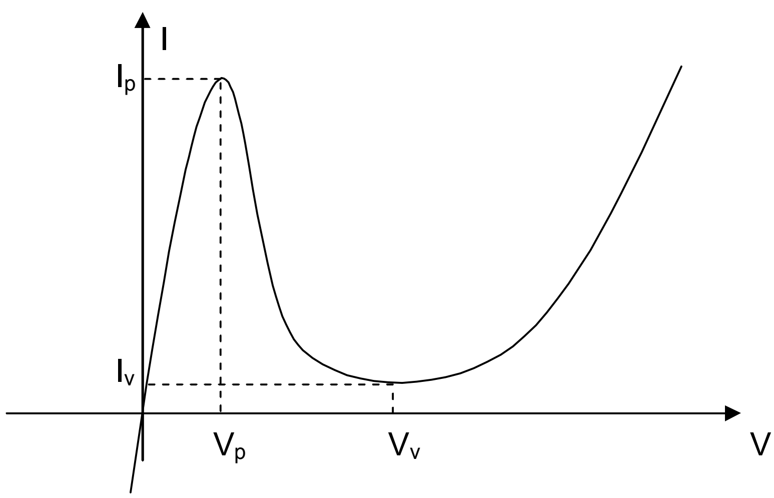

Fig.1 Current-voltage graphic characteristic of the Esaki junction

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For conventional junctions with low levels of doping, the length of the zone of barrier is relatively large and therefore in the standardized theory the considered probability is very small for which the tunnel effect practically disappears with the flattening of the graphic representation which assumes the known exponential trend like in fig.2 (continuous line).

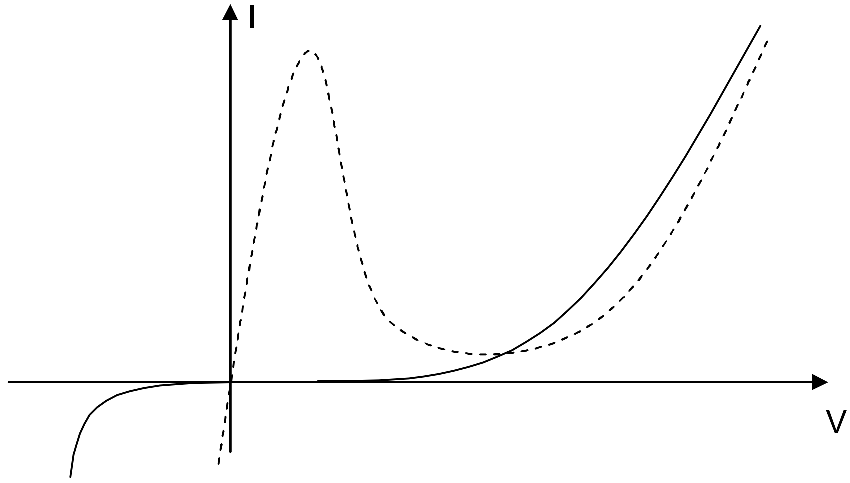

Fig.2 The continuous line represents the current-voltage graphic characteristic of the conventional junction while the dotted line is relative to the Esaki junction.

Conventional junctions with low levels of doping work generally with voltages of direct polarization around 0,2-0,3V (for germanium) and 0,7-0,8V (for silicon), the Esaki junctions work largely with smaller voltages.
In scientific literature the functioning of solid-state junctions[1] is described by means of the Fermi-Dirac statistics in which the Fermi level is the energy level whose probability to be occupied by electrons is the 50%. In the intrinsic semiconductor (without doping) it is exactly in the midst of the forbidden band which is the energy band put between valence band and conduction band. In the extrinsic semiconductor with P doping the Fermi level is closer to the valence band and in the extrinsic semiconductor with N doping the Fermi level is closer to the conduction band. In the PN junction the Fermi level is constant along the length of the junction (fig.3) and with reference to the energy bands we have

$$E_p = eV_{bo} = E_{CP} - E_{CN} = E_{VP} - E_{VN} \qquad (1)$$

where e is the electron charge, E_p is the barrier of potential energy and V_{bo} is the difference of electric potential from one end of the junction to the other in conditions of equilibrium. Applying an external direct voltage which equals V_{bo} the zone of barrier (called also zone of space charge or emptying zone) practically disappears for which it is necessary to work in normal conditions for lower voltages than V_{bo}.
Increasing the doping the length of the zone of barrier decreases and in terms of probability it facilitates the conduction of electric charges and the passage of electric current. But simultaneously with this effect the V_{bo} barrier of electric potential increases as per the Boltzmann relation in conditions of equilibrium

$$V_{bo} = \frac{K\,T}{e} \ln \frac{N_a\ N_d}{n_i^2} \qquad (2)$$

where e is the electron charge, K is the Boltzmann constant, T is the absolute temperature, n_i is the intrinsic concentration of the semiconductor, N_a is the concentration of acceptor atoms in the P zone, N_d is the concentration of donor atoms in the N zone.
The probability of conduction of electric charges in consequence of this second effect clearly decreases, but this second effect in the probabilistic interpretation of the tunnel effect isn' t taken into account. This consideration is important also because in conventional junctions with low levels of doping the direct opposite happens: in fact in these the length of the zone of barrier is larger and consequently the probability of conduction is smaller but simultaneously they have also a smaller V_{bo} potential barrier and consequently a larger probability of conduction. In conventional junctions nevertheless the probabilistic tunnel effect doesn' t happen.

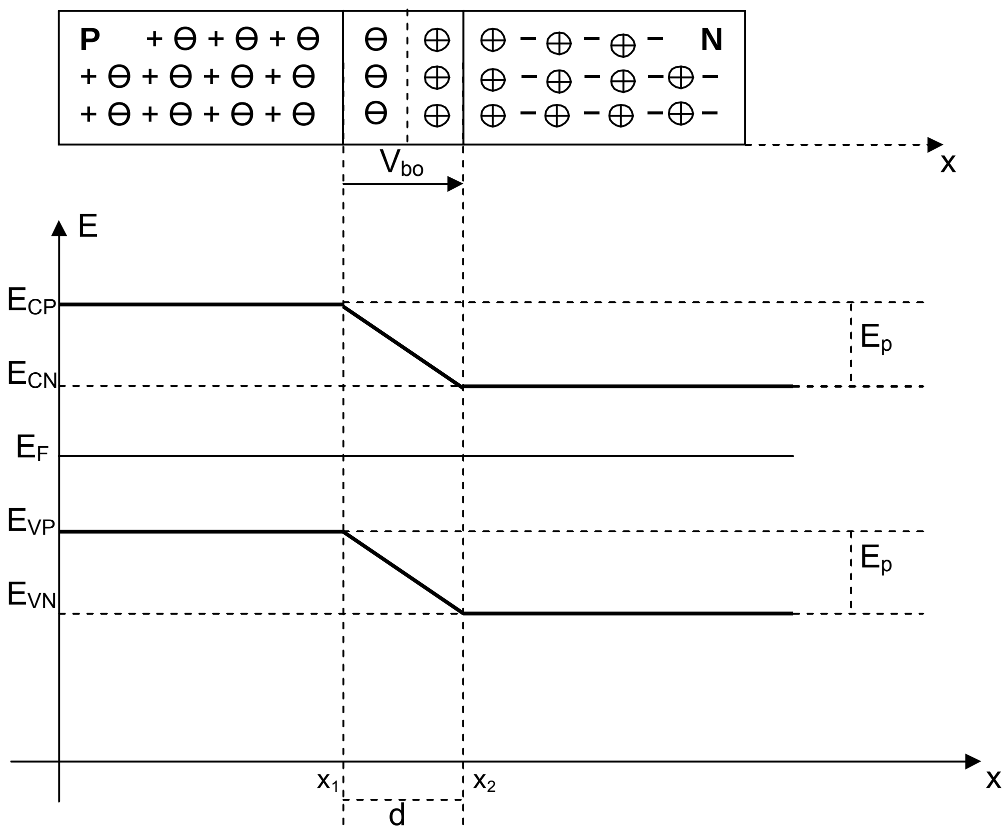

Fig.3 Energy bands in the PN junction in conditions of equilibrium (i.e. without polarization).

$d=x_2-x_1$ is the length of the zone of barrier
E_{VP} is the energy maximum level of the valence band in the P zone
E_{CP} is the energy minimum level of the conduction band in the P zone
E_{VN} is the energy maximimum level of the valence band in the N zone
E_{CN} is the energy minimum level of the conduction band in the N zone
E_F is the Fermi level which has a constant value in both the zones of the junction in conditions of equilibrium. In the Fermi-Dirac statistics the Fermi level is the energy level whose probability to be occupied by electrons is the 50% and in the intrinsic semiconductor it is exactly in the midst of the forbidden band. In the P zone the Fermi level is closer to the valence band and in the N zone it is closer to the conduction band
E_p is the barrier of potential energy.

The logical inconsistencies connected with the probabilistic interpretation of the tunnel effect require to go into the matter more thoroughly and to work out an alternative solution that discards the probabilistic interpretation and strives to give a deterministic physical explanation for the considered effect.

2. Physical properties of the Esaki junction

Let us consider the PN junction represented in fig.4 and suppose that the two zones have the same intensity of doping for which

$$N_a = N_d = N_p \qquad (3)$$

where N_p is the common concentration of doping atoms in the two zones.

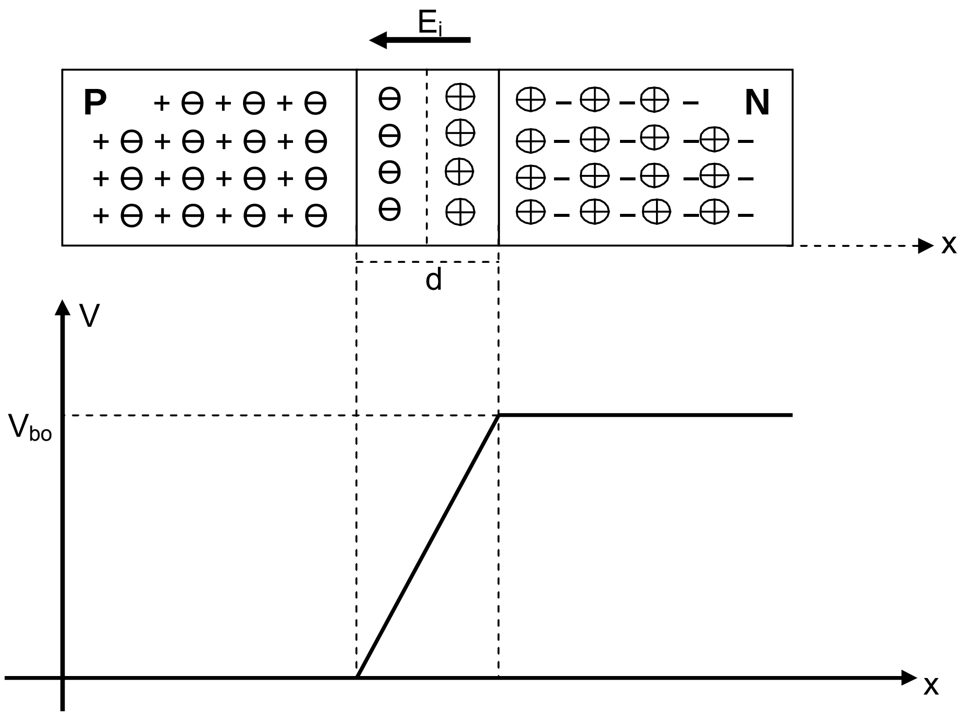

Fig.4 The background intrinsic semiconductor is tetravalent and at every temperature it has the same number of free electrons and free holes. In the P zone doping atoms are trivalent and therefore there are more positive holes than in the intrinsic semiconductor. On the contrary in the N zone doping atoms are pentavalent and therefore there are more free electrons than in the intrinsic semiconductor.
In the zone of barrier free electric charges cancel each other out and fixed electric charges generate a zone of space charge called also emptying zone.

Due to the formation of the zone of space charge an E_i electric field is born inside this zone which in conditions of equilibrium opposes the diffusion motion of free electrons from the N zone to the P zone interrupting the phenomenon of recombination between electrons and holes.
The physical situation represented in fig.4 is stationary and for Esaki junctions with high doping the electric field $E_i=V_{bo}/d$ is very intense because V_{bo} is great by reason of the (2) and d is small. In fact using the Poisson equation, from the (2) and (3) it can be deduced that

$$d = 2\sqrt{\frac{\varepsilon V_{bo}}{e N_p}} = 2\sqrt{\frac{\varepsilon}{e N_p}\,\frac{2KT}{e}\,\ln\frac{N_p}{n_i}} \qquad (4)$$

where ε is the dielectric constant. Assuming in first approximation that the emptying zone is equivalent to an electrical condenser, for (2) we have

$$E_i = \frac{V_{bo}}{d} = \frac{\frac{2KT}{e}\,\ln\frac{N_p}{n_i}}{2\sqrt{\frac{2\varepsilon KT\,\ln\frac{N_p}{n_i}}{e^2 N_p}}} = \frac{1}{2}\sqrt{\frac{2KT}{e}\,\ln\frac{N_p}{n_i}}\,\sqrt{\frac{eN_p}{\varepsilon}} \qquad (5)$$

From the previous relation we deduce that increasing the intensity of the N_p doping the E_i electric field becomes very strong: in particular for dopings of the order of $10^{19} - 10^{20}$ atoms/cm^3 that are normal in the Esaki junctions we have fields of the order of $(0,3 - 1,5)\,10^6$ V/cm. In conventional junctions with small levels of doping of the order of $10^{15} - 10^{17}$ atoms/cm^3 the electric fields are relatively weak of the order of $(2 - 30)\,10^3$ V/cm which are from 10 to 1000 times less intense than in Esaki junctions.
The typical physical property[2] of the Esaki junction is just the existence of this strong electric field in the zone of barrier which is able to break very numerous covalent bonds for field emission with the production of very numerous free electrons and holes in the zone of barrier which therefore stops being an emptying zone (fig.5). The production of electron-hole couples is the more strong the more the doping is high: this phenomenon doesn' t happen in conventional junctions with small levels of doping and weak electric fields.

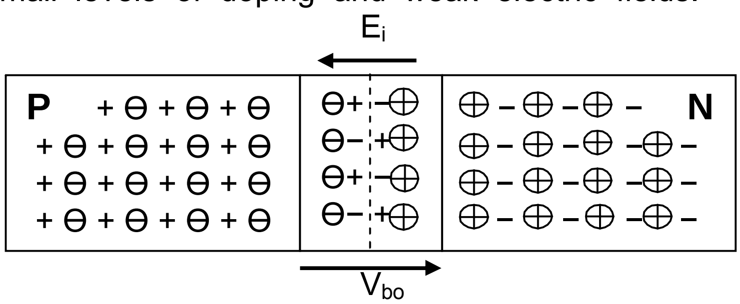

Fig.5 The high level of doping in the Esaki junctions generates in the zone of barrier a strong electric field which because of field emission produces a high number of free electron-hole couples for which the zone of barrier (zone of space charge) isn' t an emptying zone.

It is manifest that the Esaki junction is very different from the conventional junction because the zone of barrier in the Esaki junction isn' t an emptying zone and it has certainly influence on the physical behavior of the junction. In fact in the conventional junction with small levels of doping the emptying zone interrupts the electric continuity of the junction. In the Esaki junction with high levels of doping the field emission in the emptying zone generates a large number of free charges (electron-hole couples) and it restores the electric continuity of the junction.

3. Polarization of the Esaki junction and tunnel effect

For working the Esaki junction must be biased and supplying the junction with a V external voltage so as to bias directly the junction (fig.6), it is possible to observe and to measure an electric current also for small values of voltage unlike the conventional junction.

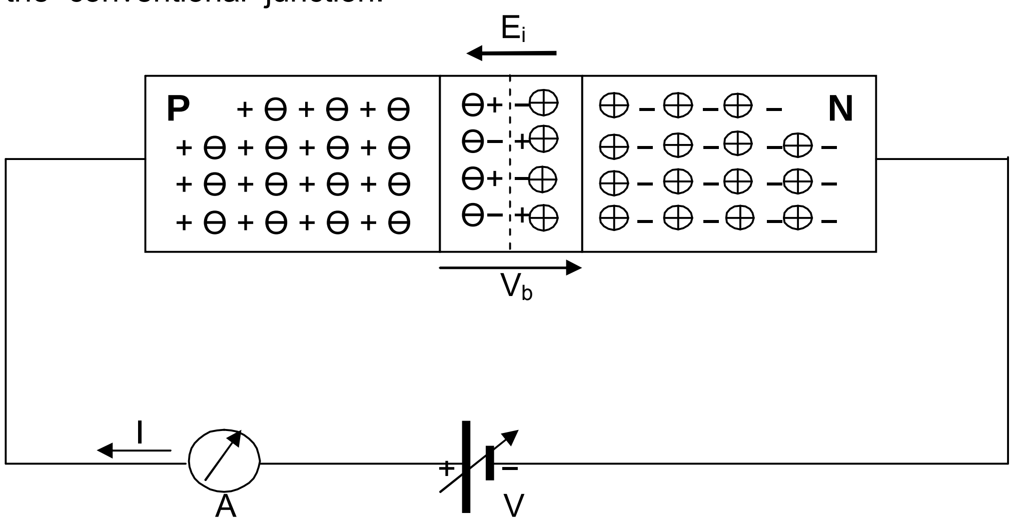

Fig.6 The junction is biased directly through a variable voltage generator which supplies the P zone with positive electric potential and the N zone with negative electric potential. The ammetter A is able to measure the electric current.

Starting from null voltage and increasing the V voltage we see that the ammetter measures a current also for small values of voltage and this current increases with the voltage. We obtain the OA portion of graph (fig.7) that has an almost linear trend because the field emission has restored the electric continuity of the junction. This portion of graph is absent in the conventional junction.

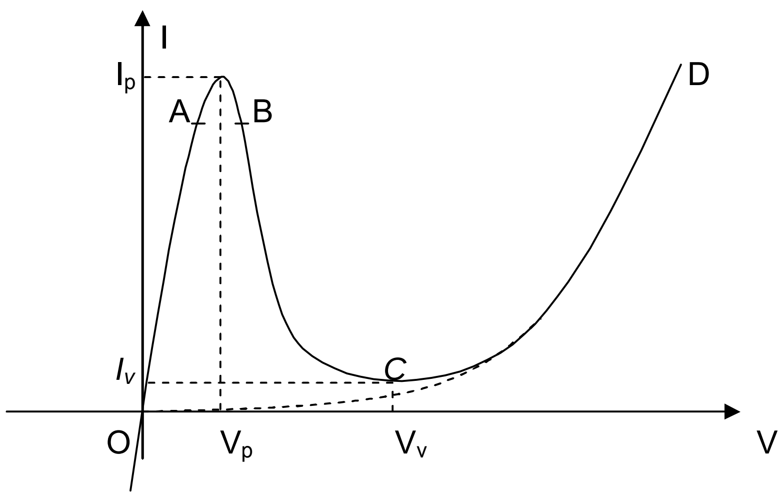

Fig.7 The OABC portion of graph in the Esaki junction represents the so-called tunnel effect which isn' t detected in the conventional junction. In quantum mechanics the tunnel effect can be explained only by the probability theory. We prove here the tunnel effect in the Esaki junction can be explained without making use of the probability theory.

Increasing further the V voltage the graph presents the AB portion where there is the I_p peak of current and the behavior of the junction in this portion is very different from the ohmic and linear trend. In fact as the V voltage increases the V_b potential barrier on the zone of space charge decreases

$$V_b = V_{bo} - V \qquad (6)$$

If in the OA portion this decrease doesn' t exert a significant influence on the behavior of the junction because of the small values of V, near to the A point the value of V begins to be significant and the V_b potential barrier decreases sufficiently because the behavior of the junction isn' t more linear. In fact the electric field inside the zone of space charge

$$E_i = \frac{V_b}{d} = \frac{1}{2}\sqrt{\frac{eN_pV_b}{\varepsilon}} \qquad (7)$$

decreases with V_b and the favourable conditions to the field emission decrease. This causes a reduction of electron-hole couples and a differential decrease of the current which after having reached the I_p value of peak begins to decrease. In the BC portion increasing further the V voltage of direct polarization this phenomenon of decrease of the current continues until the C point where the tunnel current ends completely and the Esaki junction assumes in the CD portion the typical behavior of a conventional junction.

Decreasing dopings the tunnel effect is as less evident because the field emission in the zone of space charge is more weak and currents are more small with a decrease of the current peak until its complete dissolution in the conventional junction with very low levels of doping (fig.8).

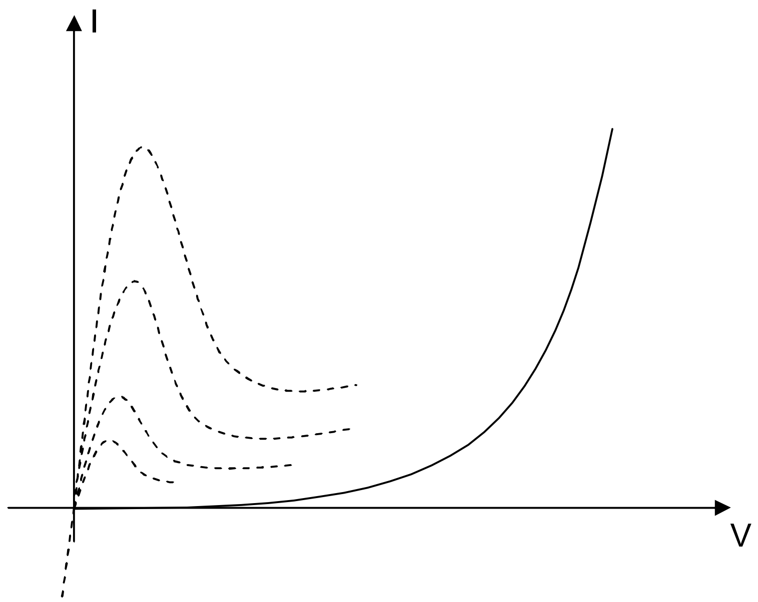

Fig.8 As levels of doping decrease also the current peak decreases until its complete identification with a conventional junction with low level of doping (continuous line).

Let us observe also that in the Esaki diodes the Zener zone[1] is characterized by very low values of inverse voltage. It confirms the existence of a very high electric field in the zone of space charge that produces field emission. In inverse polarization nevertheless (fig.9) the external voltage is additional to the potential barrier

$$V_b = V_{bo} + V \qquad (8)$$

and therefore it strengthens the electric field with electric breakdown of the junction and noteworthy increase of the inverse current. In inverse polarization therefore the Esaki effect isn' possible because increasing the inverse voltage the electric field as per (7) and (8) doesn' t decrease like in direct polarization.

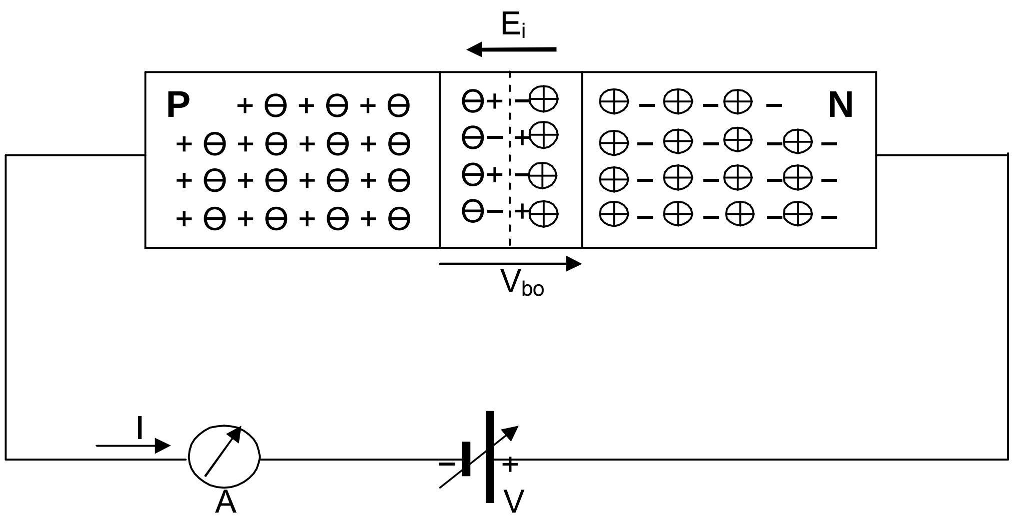

Fig.9 The junction is biased inversely through a variable voltage generator which supplies the P zone with negative electric potential and the N zone with positive electric potential.

Like this we have explained completely the physical behavior of the Esaki junction by means of deterministic physical reasonings without making use of the probability theory. Because in quantum mechanics the use of the probability theory is the consequence of the indeterminacy principle we show by this article that at least for the Esaki junction it is possible to understand and to explain the behavior of the connected physical phenomenon also without probabilistic reasonings and this represents the precondition in order to perform a critical analysis of the indeterminacy principle.

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References

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[2] D. Sasso, Teoria deterministica dell' effetto tunnel nel diodo Esaki, (on the proceedings of National Academy of Lincei, Rome, 1984)