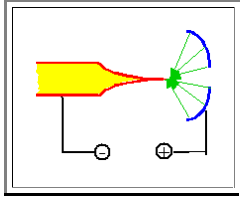


2.3.2 Field Enhanced Emission and Tunnelling Effects

If you run a **cathode**, emitting an electron beam, with **large** electrical fields between the cathode and the anode, you will find that your **workfunction** E_A seems to change to smaller values as the field strength increases.

This is called **Schottky effect**; it is observed at large field values of $(10^5 - 10^8) \text{V/cm}$.

If you apply even higher field strengths (and remember: $E = U/d$; you do not need high voltages U , only small dimensions d), E_A seems to vanish altogether.



- This effect is called **field emission**. It works even at room temperature and is barely temperature dependent, so it can not be a temperature activated process.
- Field emission is rather easy to obtain: all you have to do, is to make a very fine tip with a curvature of the tip in the **nm** - range as shown on the left.
- Field emission might then occur with a few Volts between the anode and the tip, because all the field lines will have to converge on the small tip.

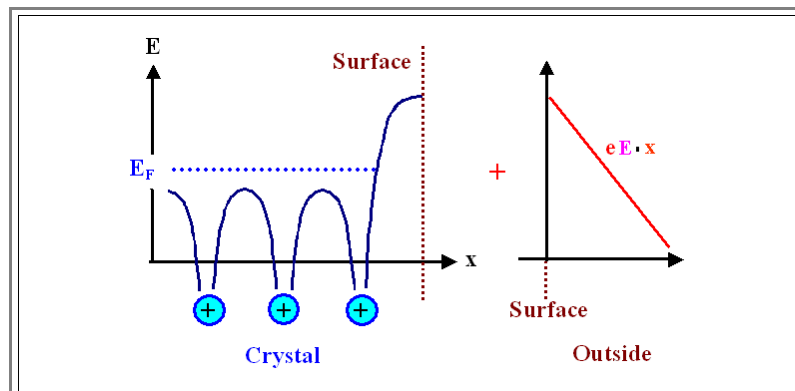
How can we understand these effects? Whereas the **Schottky effect** is relatively straight forward, **field emission** is a manifestation of the **tunnelling effect**, a purely quantum mechanical phenomenon.

Lets look at how the **free electron gas model** must be modified at high field strengths - and we will be able to account for **both** effects.

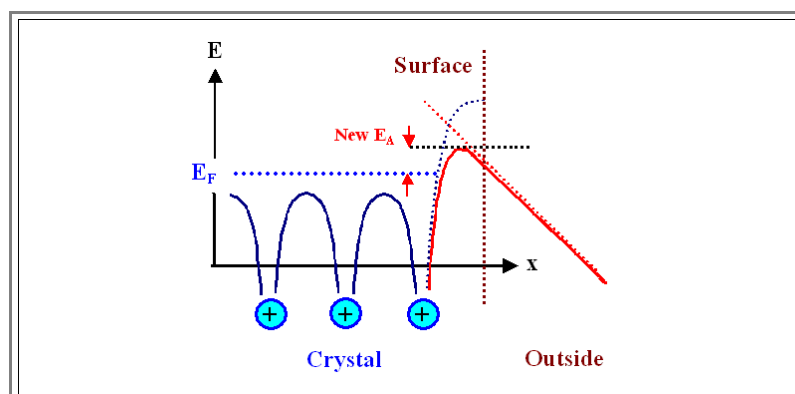
- The potential energy E outside of the material is such that electrons are to be extracted - it is not constant, but varies with the field strength E simply as

$$E = e \cdot E \cdot x$$

- E , the (constant) applied field strength (written in mauve to make sure that we do not mix it up with the energy E). We have the following situation:



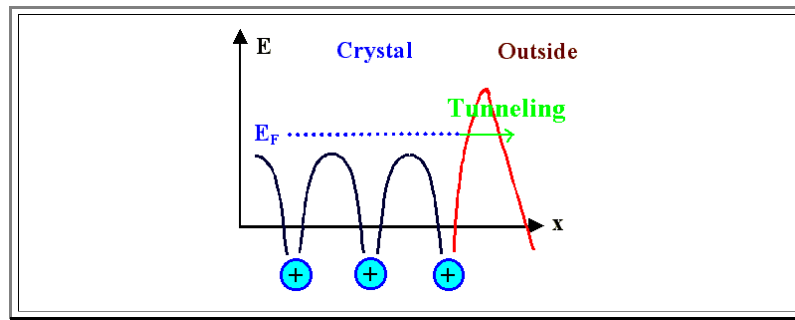
- Simply summing up the energies graphically yields the qualitative energy curve for an electron at the edge of a crystal as shown below.



- Whichever way you superimpose the potential energies, the potential barrier to the outside world will always be reduced. This explains qualitatively the **Schottky effect**.

The **field emission effect** requires a somewhat different consideration.

- Lets look at the **extremes** of the Schottky effect. For really high field strengths the potential barrier gets even lower and thinner, it may look somewhat like this:



Now the **tunneling effect** may occur. It is a phenomenon inherent in quantum mechanics and allows electron "waves" to "**tunnel**" through a potential barrier.

- In other words, the value of the **wave function** ψ for an electron does not go to zero abruptly at a potential barrier, but decays exponentially. There is then a finite amplitude for ψ **on the other side** of the potential barrier, an effect that is felt if the barrier is "thin" and low - as in the picture above. If the field strength is high enough, large quantities of electrons can directly tunnel to the outside world. More about tunnelling in the [link](#).

Field emission thus is a purely quantum mechanical effect; there is no classical counterpart whatsoever. It is used in a growing number of applications:

- Electron microscopes** for special purposes (e.g. scanning electron microscopes with high resolution at low beam voltage, a must for the chip industry) are usually equipped with **field emission "guns"**.
- "Scanning Tunnelling Microscopes" (STM)** which are used to view surfaces with atomic resolution, directly employ tunnelling effects.
- Large efforts are being made to construct flat panel displays with millions of miniature field emission cathodes - at least one per pixel.
- Some semiconductor devices (e.g. the **"tunnel diode"**) depend on tunnelling effects through space charge regions.

In other contexts, tunnelling is not useful, but may **limit** what you can do. Most notorious, perhaps, is the effect that **very thin** insulators - say **5 nm** and below - are insulating no more, a growing problem for the chip industry.

Questionnaire

Multiple Choice questions to 2.3.1
and 2.3.2