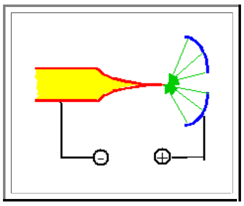
2.3.2 Field Enhanced Emission and Tunnelling Effects

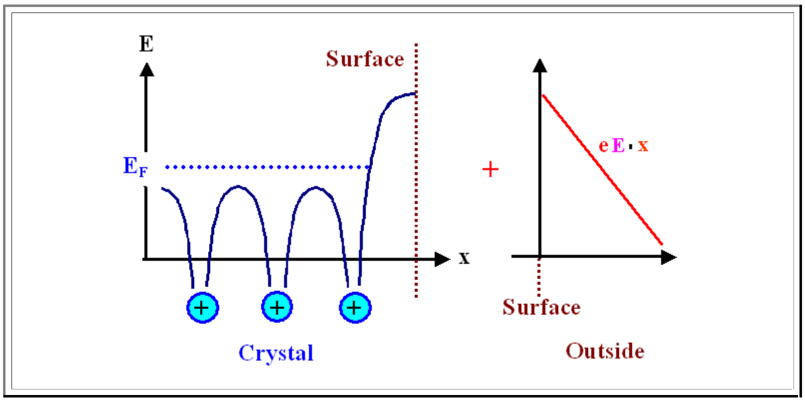
- If you run a **cathode**, emitting an electron beam, with *large* electrical fields between the cathode and the anode, you will find that your workfunction E_A seems to change to smaller values as the field strength increases.
  - This is called **Schottky effect**; it is observed at large field values of **(10^5 - 10^8)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.



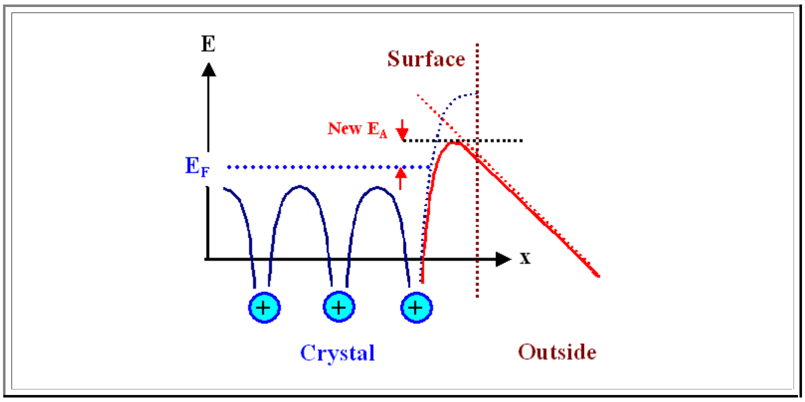
  - This effect is is called **field emission**. It works even at room temperature and is barely temperature dependent, so it can not be a temperature activated process.
  - Field emission is rather easy to obtain: all you have to do, is to make a very fine tip with a curvature of the tip in the **nm** - 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

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

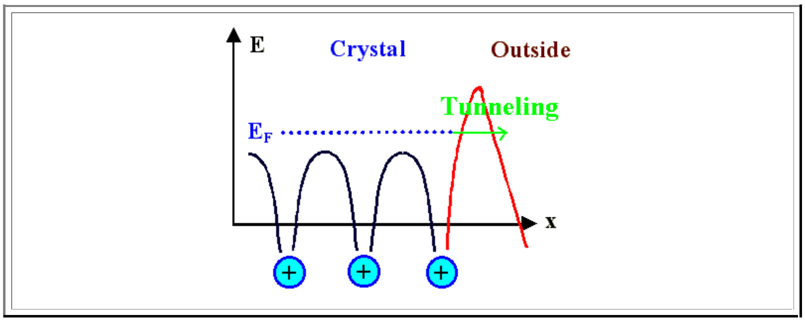
  - E, the (constant) applied field strength (written in mauve to make sure that we do not mix it up with the energy E). We have the following situation:



  - 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 got 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.

Questionaire
Multiple Choice questions to 2.3.1 ***and*** **2.3.2**