Background: Electron Spin Resonance, a Qualitative Introduction

There is only one technique available with the demonstrated analytical power and the sensitivity to identify electrically active atomic scale defects in semiconductor systems: electron spin resonance (ESR). [1-29]. The technique is also sometimes called electron paramagnetic resonance (ESR). ESR studies have identified dozens of trapping defects which can limit the performance of semiconductor devices. ESR is sensitive to trapping centers with an odd number of electrons in semiconductors and insulators [1] as well as in semiconductor/insulator interfaces.[9,14,16,17] Although a comprehensive explanation of the technique would requires a fairly lengthy discussion, the basic idea is simple. A trap which captures an electron or a hole has an odd number of electrons either before charge capture or after capture. Since ESR is sensitive to sites with an odd number of electrons, it can detect nearly all traps. (Why specify only nearly all? One could imagine a trap capturing two electrons.)

In ESR measurements, one places a sample in a large slowly varying magnetic field. The unpaired electron responds to the magnetic field somewhat like a compass needle. (The electron is a very small magnet confined to a point, a lot like the compass needle.) This admittedly imperfect but instructive analogy is illustrated in Figure 1. A compass needle will briefly oscillate when the compass is set down. There is a torque on the needle when it's not pointing north. No torque exists when it points north, but when it swings to north it's built up some momentum. As it swings past north, the torque builds up again, the process repeats itself till friction damps out the oscillations.

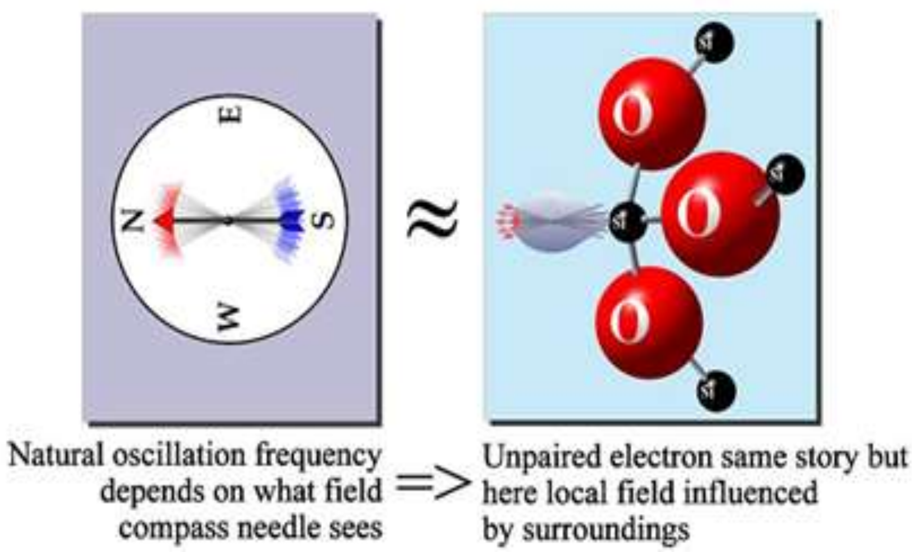

Figure 1. A simple analogy for a trapped electron exposed to a large magnetic field: a compass needle.

Suppose we were to increase the field experienced by the compass needle; the compass needle oscillation frequency would increase because the torque would increase. It can, e, be shown that the frequency is proportional to the field the compass needle experiences. The analogy holds for the trapped electron. An increasing magnetic field results in an increase in oscillation frequency. This frequency scales with the field which the electron actually experiences. Since the electron in the trap doesn't experience friction, the oscillations continue forever.

The trick in ESR is to apply a second oscillating field at fixed microwave frequency perpendicular to the applied field. When the fixed frequency matches the electron oscillation frequency, resonance occurs and energy is absorbed by the electron spin. Remember that resonance occurs at a fixed relationship between the microwave frequency and the field the electron *actually experiences*. That field is the sum of the applied field and the local field due to the surrounding atoms. If we know the frequency with high precision (we do) and we know the applied field with high precision (we do) we can work backwards to calculate the local field. From knowledge of the local field we can identify the atomic scale structure of the defect site. By measuring the amount of microwave energy absorbed by the sample we can count the number of defects of each type within the sample. The sensitivity of the conventional ESR measurement is about 10^{10} /cm^2. In conventional ESR measurements, the precision in defect counting is about 10% in relative number and somewhat better than a factor of two in absolute number. By comparing ESR measurements (which count defect densities) with electrical measurements (which count various trap densities) one can identify the physical and chemical nature of the defects responsible for traps.

The obvious limitations of conventional ESR detection in studies of semiconductor device problems are twofold: (1) to separate out only those defects which play important roles in device operation and (2) to make the measurements in actual devices in which the total number of defects may be less than the defect limit of conventional ESR. These problems can be addressed with electrically detected magnetic resonance (EDMR) typically utilizing spin dependent recombination (SDR).[3-13] In order to understand the techniques and their capabilities, we need to look more closely at the physics behind magnetic resonance.

*References in text can be found on page labeled "*References*" on website*