Magnetism and magnetization dynamics in thin film ferromagnets

Verhagen, T.G.A.

Author: Verhagen, T.G.A.
Title: Magnetism and magnetization dynamics in thin film ferromagnets
Issue Date: 2014-02-26

CHAPTER 1

Radiation & Spins

From the end of the 19th century, the light bulb that was (re-)invented by many scientist during the 19th century, started slowly to replace the traditional lightning where fossil fuels, oil, fat and wood where burnt. The light that a light bulb generates is controlled by the temperature of the filament inside the bulb. The intensity I of the emitted radiation at a wavelength λ can be described by Planck's law

$$I(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right) - 1}, \tag{1.1}$$

where T is the temperature of the blackbody, h is Plancks constant, c is the speed of light and k is Boltzmann's constant. In Figure 1.1, the intensity of the emission of a black body with a temperature of 2800 K, a 60 W incandescent light bulb and a white light emitting diode (LED) are shown. Clearly visible is that the maximum intensity of the spectrum is at approximately 1000 nm and only a small fraction (approximately 10 %) of the intensity is emitted at the visible spectrum (390 - 700 nm). To increase the efficiency of a light bulb, a much higher temperature is needed.

During the introduction of the light bulbs, also the first observations of what we now know as a light emitting diode (LED) were reported [2].

Round, one of Marconi's assistants, in 1907 published a short note in 'Electrical world' [3] (see Figure 1.2.a) where he described a 'bright glow' from a SiC crystal. In 1928, Losev published the current-voltage

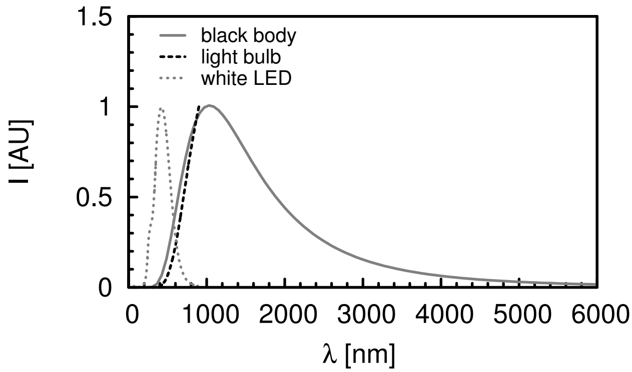
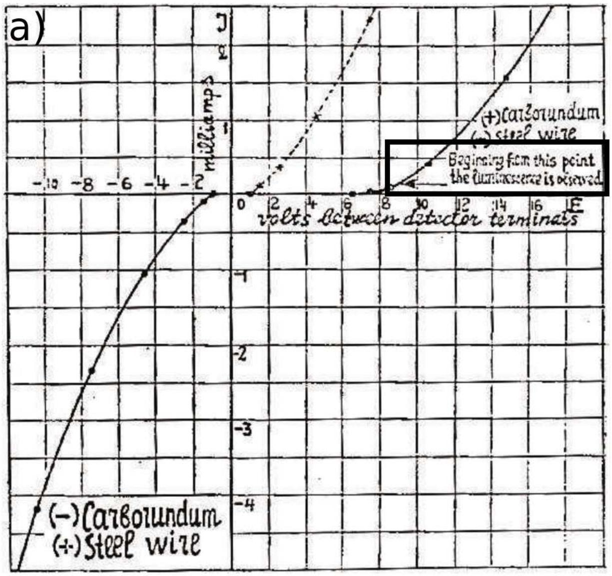


Figure 1.1: Emission spectra of an incandescent light bulb (Airam, long-life 60 W, 2800 K [1]), a white LED (Hewlett Packard HLMP-CW31 [1]) and a black body at 2800 K.

characteristic of SiC and also observed light emission, as is indicated in the current-voltage characteristic in Figure 1.2.b [4]. Unfortunately, this research was forgotten. In 1962, four research groups published papers where they showed a LED laser based on electron-hole recombination in the direct semiconductors GaAs [5–7] and GaAsP [8].

1.1 Light-emitting diodes

Depending on the type of the semiconductor, the electron-hole recombination can happen in a direct or indirect transition. In an direct band gap semiconductor (see Figure 1.3.a) the momentum of the electrons in the conduction band and the holes in the valence band is the same, whereas in a indirect band gap semiconductor (see Figure 1.3.b) these momenta are not the same. When an electron-hole recombination happens, the momentum and energy need to be conserved. In a direct band gap semiconductor, the momentum is conserved and the energy is conserved by emitting a photon with the energy equal to the band gap. In an indirect semiconductor, a photon can also be emitted if the momentum is conserved by the creation or annihilation of a phonon. However, in an indirect semiconductor these radiative recombinations are only a very small fraction of the total amount of recombinations.



b)

A Note on Carborundum.

To the Editors of Electrical World:

SIRS:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

NEW YORK, N. Y. H. J. ROUND.

Figure 1.2: a) The current-voltage characteristics of a carborundum (SiC) detector. The arrow (in the black rectangle) indicates the voltage where light emission was observed. b) A note from 1907 from the Marconi lab, mentioning that a curious phenomenon happens when 10 V was applied between two points on a carborundum crystal: the emission of a yellowish light. Images adapted by permission from Macmillan Publishers Ltd [2], © (2007).

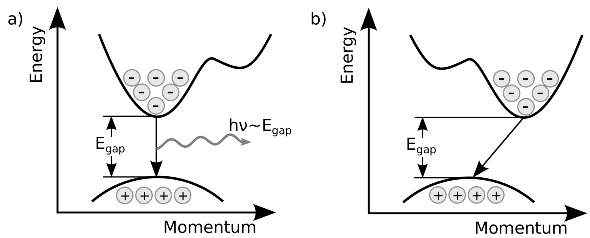


Figure 1.3: The energy of a direct (a) and an indirect (b) band gap semiconductor as a function of the momentum. In a direct band gap semiconductor, an electron can be moved from the lowest state in the conduction band to the highest state in the valence band without a change in momentum. The energy is conserved by the emission of a photon with the energy of the band gap. In an indirect band gap semiconductor, also a change in momentum is needed to move between the lowest state of the conduction band and the highest state of the valence band.

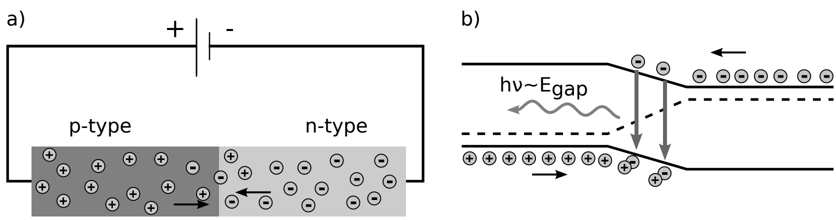


Figure 1.4: a) A p-n junction with an applied bias. When the p-n junction is forward biased (b), electrons from the n-doped region and holes from the p-doped region flow to the depletion layer, where the electrons and holes will recombine and emit a photon. Adapted from [9].

Furthermore, the conductivity of a semiconductor can be modified to create an excess of electrons (becoming an n-type semiconductor) or a deficiency of electrons (becoming a p-type semiconductor) by various techniques (for example doping or gating).

In a forward biased p-n junction (see Figure 1.4), electrons from the n-doped region flow in the p-doped region and holes from the p-doped region flow into the n-doped region. Within a characteristic diffusion length from the depletion layer, the carriers recombine. If this process happens in a direct semiconductor, the electron in the conduction band will fall into the valence band and emits a photon to conserve energy.

When the p-n junction is very heavily doped, the bottom of the n-

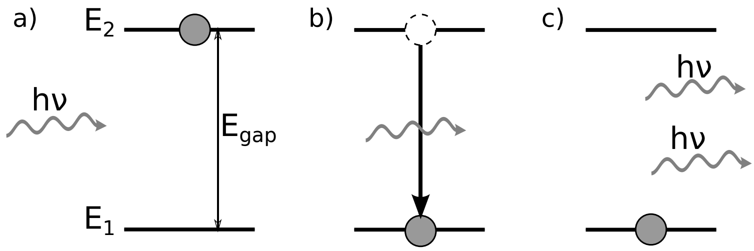


Figure 1.5: a) An electron is in the excited state E_2 and can relax to the ground state by emitting a photon. This relaxation can be induced by another photon (b), which results in two coherent photons (c). Adapted from [10].

side conduction band overlaps the top of the p-side valence band. Applying a forward bias cancels the thermal equilibrium potential difference causing the injecting of electrons from the conduction band on the n-side into the conduction band on the p-side. The injection from electrons into the conduction band on the p-side creates a situation where there are more electrons in the conduction band than in the valence band; a population inversion.

1.2 Semiconductor laser

An electron in the excited state will finally relax to the ground state by emitting a photon. If this happens in the absence of any external field, this is called a spontaneous emission, where the generated photons are non-coherent.

However, the relaxation can also be induced by a photon, as is shown in Figure 1.5. This process is called stimulated emission and the emitted photons are coherent. Whenever more electrons are in the excited state than in the ground state, one incident photon can trigger an avalanche of photons: light amplification by stimulated emission of radiation or laser. This avalanche continues as long as the population inversion can be maintained. Typically frequencies of the emitted radiation are of the order of the bandgap, which is typically 1 – 5 eV. This corresponds to 250 – 1250 THz.

1.3 THz gap

The electromagnetic frequency range used nowadays is large, from the Hertz via the kilohertz, megahertz, gigahertz up to the terahertz. Semiconductor devices are enabling components for almost the whole frequency range. For the low frequency range, semiconductor transistors and other devices based on electron transport produce the radiation, whereas semiconductor lasers generate coherent light at very high frequencies.

As shown in Figure 1.6, there is no continuous transition from the low frequency to the high frequency region and between these two regimes lies the so-called THz gap. On the one hand, transistors and other devices based on electron transport are limited to about 300 GHz. On the other hand, the wavelength of semiconductor lasers can be extended down to only 30 THz. In the lab, many different THz sources are explored, that are shown as ovals in Figure 1.6. Unfortunately, most of these devices work well at (very) low temperatures, but at room temperature the output power reduces considerably.

1.4 Spintronics

During the last 30 years, another property of the electron became more and more popular in electronics: the spin. Spin transport electronics, or spintronics, can nowadays be found in many electronic devices. In particular, spintronics found its way in data storage and manipulation devices such as the read/write head of a harddisk, magnetoresistive random-access memory (MRAM) and spin-transfer torque random-access memory (STT-RAM). The wish to increase the speed, the storage capacity and decrease the power consumption leads to a constant flow of new spintronic phenomena like the spin transfer torque [12, 13], spin-orbit torques [14] ('Spin-Orbitronics'), the spin Hall effect [15], the spin Seebeck effect [16] and 'plasmonic spintronics' [17].

1.5 Outlook

In 2004 Kadigrobov [18, 19] proposed the idea that electromagnetic radiation might be created when a LED and the spin of the electron are combined: a spin-flip laser. In a spin-flip laser, a photon is created when a spin-flip process takes place in a normal metal or ferromagnet. A very promising feature of the spin-flip laser is the prediction that the laser emits light in the terahertz range. In **Chapter 2**, an introduction

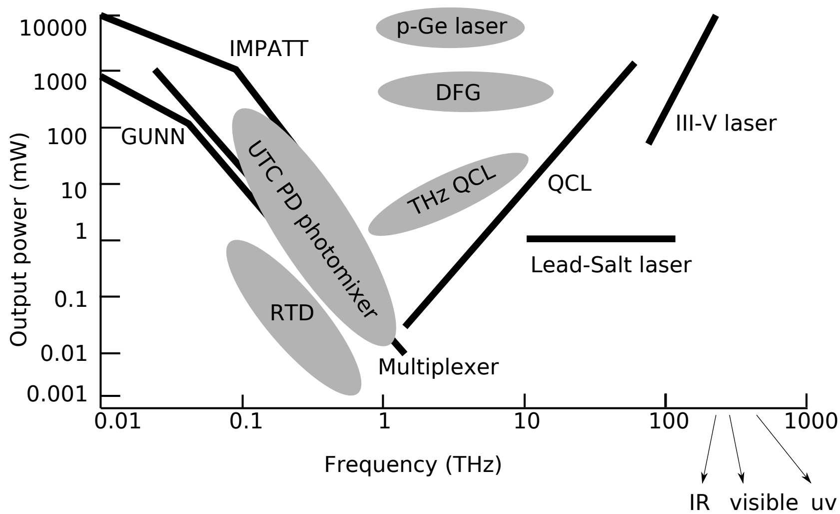


Figure 1.6: THz (10^{12} Hz) emission power as a function of frequency. The solid lines indicate conventional THz sources; IMPATT stands for impact ionization avalanche transit-time diode, multiplexer is a Schottky barrier diode frequency multiplier, QCL is a quantum cascade laser and III-V laser is a semiconductor laser diode. The ovals denote recent THz sources, where RTD stands for resonant tunnelling diodes, UTC-PD photomixer stands for uni-travelling-carrier photodiode photomixer and DFG stands for difference-frequency generation. Images adapted by permission from Macmillan Publishers Ltd [11], © (2007).

to spintronics is given, which will lead to the introduction of the spin-flip laser. One way to build and characterize a spin-flip laser is via the point contact spectroscopy technique. In **Chapter 3**, this technique will be introduced and we will discuss the possibilities and limitations of this approach. Another requirement for spin-flip lasers are hard magnetic materials. **Chapter 4** describes the growth and characterization of thin films of the hard ferromagnet Sm-Co.

In **Chapter 5**, we study how the transport of spin happens at a ferromagnet/normal metal interface using ferromagnetic resonance and the spin pumping technique. Especially, we are interested in the low temperature behaviour of spin currents flowing from the ferromagnet into the normal metal. In **Chapter 6** we show what happens with the magnetization dynamics of a very thin ferromagnetic layer that has asymmetric interfaces.