SILICON CARBIDE FOR SINGLE-SPIN SENSING AND COMPUTATION

PHYS 522/ECE 695 LECTURE NOTE

APRIL 6, 2014

1. INTRODUCTION

This lecture note is based off a presentation by Abram L. Falk *on engineered defects in wide band-gap semiconductors for single-spin sensing and computation* (the presentation slides [1] are available on www.nanohub.org). Abram started out by talking about wide-gap semiconductors and their uses (Section 2). After that, he moved on to talk about Nitrogen-Vacancy Center in Diamond (Section 3) and then he switched gears to talk about Silicon carbide which he believed was an alternative to Diamond (Section 4). He wrapped up his talk by focusing on electron spin control with electric fields and strain (Section 5).

2. WIDE BAND-GAP SEMICONDUCTORS

Wide band-gap semiconductors are semiconductors with band-gap around 3 – 5 eV. In the process of trying to get rid of defects in semiconductors, people have studied a lot of wide band-gap semiconductors lately. Their applications include solid-state lighting (Gallium nitride), power electronics (Silicon carbide and Gallium nitride), etc. In fact, a recent article on www.energy.gov mentions that the US government is taking the initiative to make wide band-gap semiconductor-based power electronics cost competitive with silicon chips in 5 years [2]. A comparison among different materials is shown in Fig. 1.

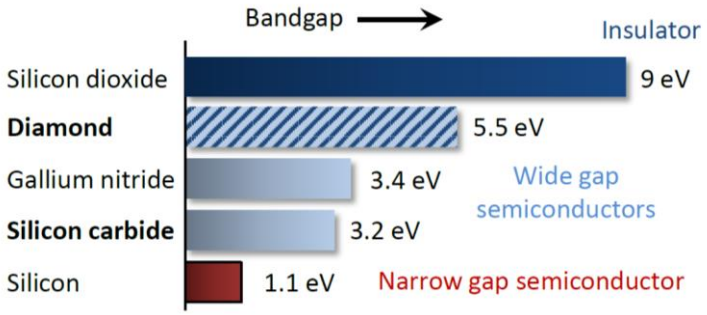

Fig. 1. Wide band-gap, narrow band-gap and insulator energies compared (Obtained from [1]).

A lot of the properties of wide band-gap semiconductors desirable for power electronics also make them ideal for quantum information. For example, in power electronics, high band-gap materials because of their high breakdown strength are suitable for high frequency electronics, while in spin qubits, the high band-gap helps in the electronic isolation of deep-level defects and allows visible and near-infrared defect addressability [1]. Another example is that in power electronics, the stiff crystal in high band gap materials leads to high thermal conductance (good for heat dissipation) while in spin qubits, stiff crystal contributes to room-temperature quantum coherence [1].

3. DIAMOND NITROGEN-VACANCY (NV) CENTER

The NV center in diamond consists of a lattice in which one carbon atom is replaced by a nitrogen atom and its neighbor is a vacant space left by another carbon atom. The localized electronic state bound to the NV center has a paramagnetic triplet ground state, hence, it has a potential to be used as a single-spin memory for quantum memory [3]. The spin coherence times at room temperature can go from 10 μs up to 2 ms (depending on the purity of the diamond), which makes it desirable for quantum computing and communication [1]. To learn more about NV centers in diamond, please refer to [3] and Lecture S1 notes compiled by Joseph Lukens, where he introduces the basics, their key properties and capabilities.

Challenges with NV centers in diamond include creating high quality spins in nanodiamonds (because of phonon side-band as shown in Fig. 2), narrowing optical emission and processing the diamond.

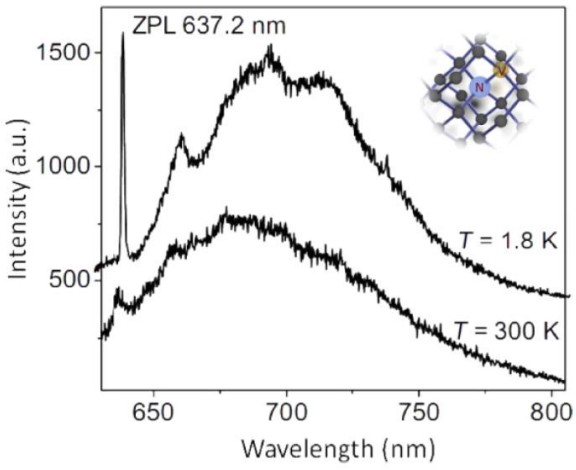

Fig. 2. NV center fluorescence spectrum showing phonon side-band (Obtained from [1])

4. SILICON CARBIDE

Silicon carbide is not an earth-abundant material but is readily grown. It and comes in more than 200 crystal types also known as polymorphs – the 3 commonest types are 4H, 6H and 3C; the different polymorphs have different band-gaps, different electronic properties and distinct but related defect states. Also, there is an availability of epitaxial films on top of Silicon carbide and Silicon carbide can also be used as an epitaxial film. All these are properties that diamond does not have; nevertheless, Silicon carbide resembles diamond in many ways and even looks like diamond to the human eye. Divacancy (a missing Carbon atom next to a missing Silicon atom) in Silicon carbide is comparable to an NV center in diamond as depicted in Fig. 3.

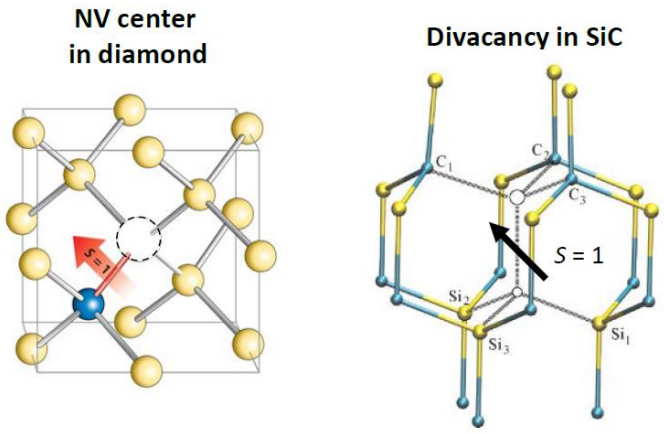

Fig. 3. Visualization of the NV center in diamond compared to divacancy in Silicon carbide (Obtained from [1])

Some common features between divacancy in Silicon carbide and NV center in diamond are that they are useful for optical spin polarization and readout, they both have long spin coherence times that persist at room temperature and both defects are comprised of a 6-electron state.

Measurement studies on the divacancies in 4H, 6H and 3C – Silicon Carbide are discussed briefly in Sections 4.1, 4.2 and 4.3. For more information on these studies, reader should refer to [4].

4.1. Photoluminescence Measurements

Photoluminescence of the divacancy defects in 4H, 6H and 3C – Silicon Carbide are is shown in Fig. 4. It is important to note that the photoluminescence peaks are in the near IR and approaching 1550 nm which is important for different applications including photonics.

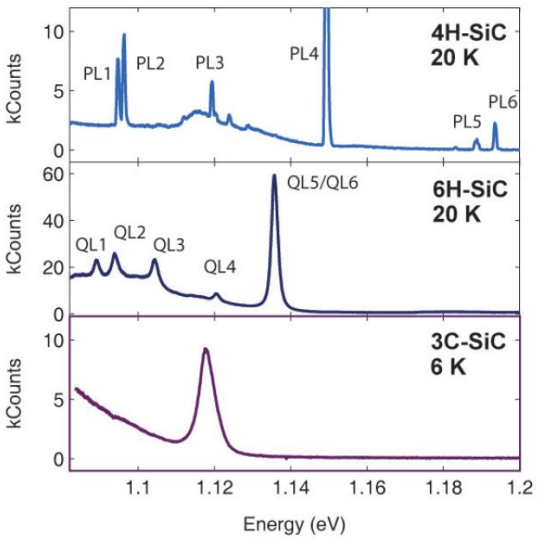

Fig. 4. Photoluminescence spectrum of the divacancy defects in the 4H, 6H and 3C – SiC (Obtained from [1, 4]).

4.2. Optically Detected Magnetic Resonance (ODMR) Measurements

ODMR measurements for 4H, 6H and 3C – SiC are shown in Fig. 5. The change in the fractional change in photoluminescence is a signature of spin flips – this is when the frequency is resonant with one of the defect's spin transitions [4]. The multiple ODMR lines shows how SiC can be flexible for optically addressable spin states [4].

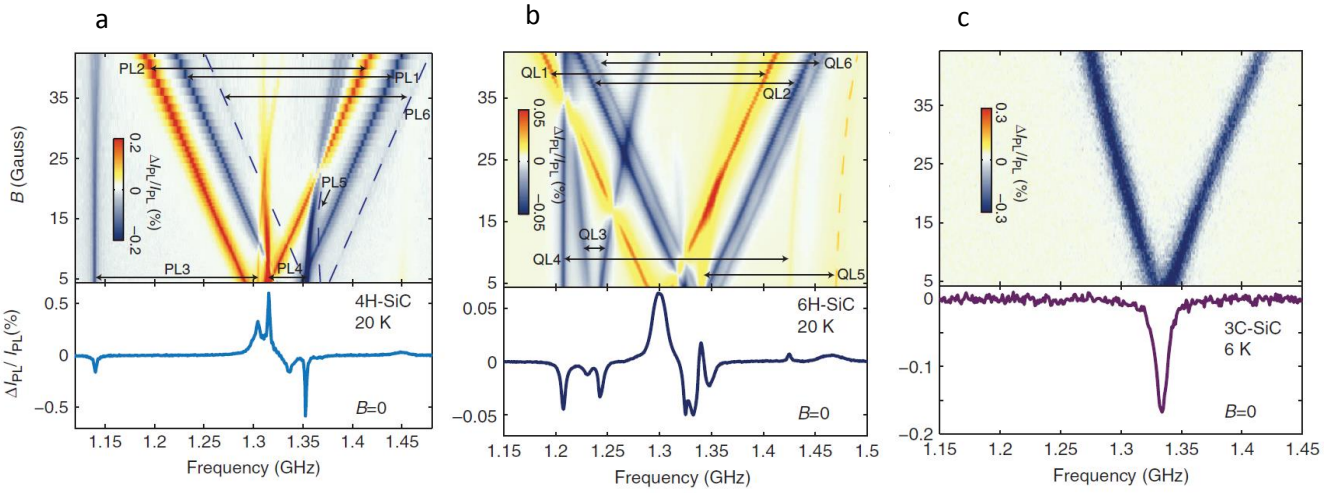

Fig. 5. ODMR Spectrum of (a) 4H-SiC (b) 6H-SiC (c) 3C-SiC. Bottom plot is the fractional change in amount of photoluminescence vs frequency. Top plot is 2D plot of the fractional change in the amount of photoluminescence as a function of magnetic field and frequency (Obtained from [4]).

4.3. Pulsed Measurements

Pulsed measurements in the form of Hahn-echo measurements for 4H-SiC is shown in Fig. 6. Results for 6H and 3C-SiC can be found in [4].

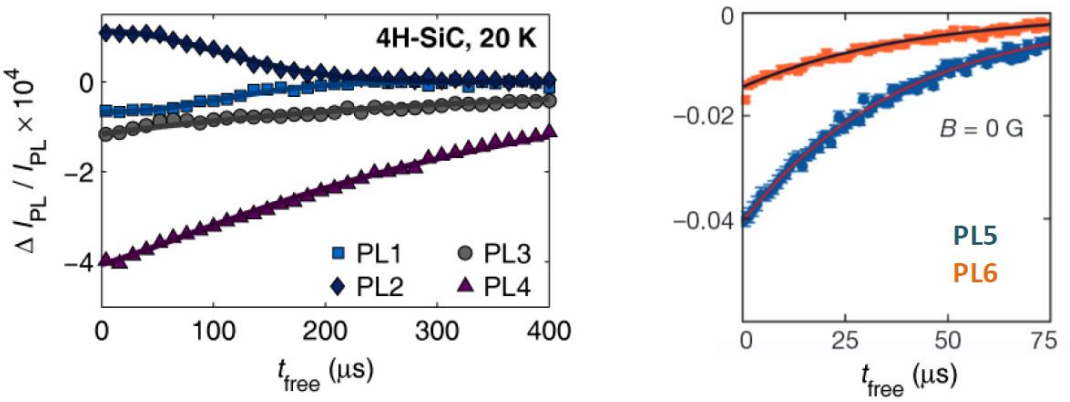

Fig. 6. Hahn-echo measurements for 4H-SiC at (a) temperature of 20 K (b) room temperature (Obtained from [1]).

At 20 K, it can be seen that T_2 times last up to 350 μs while at room temperature, the T_2 times last up to 50 μs. The long spin coherence time is comparable to that of NV centers in diamonds, thus making it desirable for quantum information.

5. CONTROLLING ELECTRON SPINS WITH ELECTRIC FIELDS AND STRAIN

Abram and his colleagues observed the effects of electric fields and strain on neutral divacancies in 4H-SiC [5]. In order to strain the crystal uniaxially, they thinned 500 μm-thick chips of SiC down to 50 μm-thick membranes and then put them either between electrodes or mounted them on piezos. After that, they applied some perturbation to see if it shifts the spin transition energies. They found that SiC has 2-7 times stronger spin response to electric fields compared to NV centers in diamond and a strain sensitivity of 10^{-7} strain/√Hz/spin. More on this topic can be found in [5].

Furthermore, Abram and his colleagues showed that AC electric fields can be used to coherently drive the spin of optically addressable point defects in SiC [6]. They were motivated by the fact that electric fields are more confinable than magnetic fields. Please, refer to [6] for details.

REFERENCES

[1] A. Falk, "Engineered Defects in Wide Band-gap Semiconductors for Single-spin Sensing and Computation." https://nanohub.org/resources/20739.

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[3] V. Acosta and P. Hemmer, "Nitrogen-vacancy centers: Physics and applications." *MRS Bulletin* **38**, 127 (2013).

[4] A. Falk, B. Buckley, G. Calusine, W. Koehl, V. Dobrovitski, A. Politi, C. Zorman, P. Feng, and D. Awschalom, "Polytype control of spin qubits in silicon carbide," *Nat. Comm.* **4**, 1819 (2013).

[5] A. Falk, P. Klimov, B. Buckley, V. Ivady, I. Abrikosov, G. Calusine, W. Koehl, A. Gali, and D. Awschalom, "Electrically and mechanically tunable electron spins in silicon carbide color centers," *arXiv:* 1311.6832 (2014)

[6] P. Klimov, A. Falk, B. Buckley, and D. Awschalom, "Electrically Driven Spin Resonance in Silicon Carbide Color Centers," *Phys. Rev. Lett.* **112**, 087601 (2014).