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**Superexchange and spin-orbitronics in nitride semiconductors**

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Besides their indisputable significance for optolectronics and high power electronics, gallium nitride (GaN) and related alloys possess also a number of features attractive for spintronic and spin-orbitronics, enabling, in particular, spin-charge interconversion *via* spin-orbit coupling associated with inversion asymmetry and leading to a sizable Rashba field and piezoelectric properties.

On degenerate *n*-doped wurtzite GaN:Si films grown on semi-insulating GaN:Mn buffer layers by metal-organic vapor phase epitaxy (MOVPE), we have determined the magnitude of the Rashba parameter $\alpha_R$=(4.5±1) meV Å from antilocalization magnetotransport studies carried out at millikelvin temperatures [1]. This value of $\alpha_R$ indicates, that in previous studies on electrons in proximity of GaN/(Al,Ga)N interfaces, bulk inversion asymmetry was dominant over structural inversion asymmetry. The comparison of experimental and theoretical values of $\alpha_R$ across a series of wurtzite semiconductors is presented as a test of current relativistic *ab initio* computation schemes [1].

Spin pumping, *i.e.,* the generation of spin currents under ferromagnetic resonance conditions, is an efficient mechanism for the inception of spin current and its conversion into charge current in non-magnetic metals or semiconductors *via* spin Hall effects. We have demonstrated the generation of pure spin current in bilayers of permalloy and *n*-GaN:Si – at room temperature and through spin pumping [2]. We have found for *n*-GaN:Si a spin Hall angle $\theta_{SH}=3.03\times10^{-3}$, exceeding by one order of magnitude those reported for other semiconductors,and pointing at III-nitrides as particularly efficient spin current generators.

Moreover, it is generally accepted that exchange interactions mediated by itinerant holes account for ferromagnetism in semiconductors doped with transition metals (TM). However, a number of dilute magnetic semiconductors, such as (Ga,Mn)N, and topological insulators, like $(Sb,V)_2Se_3$ are ferromagnetic despite the absence of carriers.

In order to shed light on the origin of this ferromagnetism, we have developed a comprehensive growth and characterization protocol aiming at developing high quality epitaxial (Ga,Mn)N layers by MOVPE [3,4] and by molecular beam epitaxy [5,6]. Single-crystalline wurtzite films with a concentration x up to 10% of Mn randomly distributed mostly in substitutional lattice sites and in the charge state $Mn^{3+}$ are obtained. In contrast to donor-compensated samples with $Mn^{2+}$ found in literature and showing antiferromagnetic coupling between the Mn spins, our epilayers are ferromagnetic. The magnetic phase diagram as determined by SQUID measurements down to 50 mK, gives a $T_C$ up to 13 K for x = 10%, and $T_C \sim x^{2.2}$, pointing to a short range exchange interaction $J(r) \sim r^{-6.6}$.

By implementing the Paramenter Hamiltonian, the Jahn-Teller distortion, and the tight binding model [4,6,7], we obtain a consistent description of the experimental phase diagram [6] and assign the coupling mechanism to a superexchange interaction, that can be ferromagnetic for partly filled hybridizing orbitals of the TM ions ($t_2$ in our case). The magnetic properties of (Ga,Mn)N are thus entirely different from the case of

(Ga,Fe)N, in which - according to our studies - $T_C > 300$ K independently of $x$ [8]. This dissimilarity can be traced back to results of ab initio studies indicating that Fe cations, in contrast to the Mn ones, tend to aggregate at the growth surface [9], so that the magnetic properties of (Ga,Fe)N are determined by the magnetism of the resulting self-assembled Fe-rich nanocrystals embedded in the GaN matrix.

Furthermore, we have demonstrated – by direct magnetization measurements – the electrical control of the magnetization in wurtzite (Ga,Mn)N [10]. In this dilute magnetic insulator the Fermi energy is pinned by Mn ions in the mid-gap region, and the $Mn^{3+}$ ions show strong single-ion anisotropy. We have established that (Ga,Mn)N sustains an electric field up to at least 5 MV/cm, indicating that Mn doping turns GaN into a worthwhile semi-insulating material. Under these conditions, the magnetoelectric coupling is driven by the inverse piezoelectric effect that stretches the elementary cell along the *c*-axis and, thus, affects the magnitude of the magnetic anisotropy. In this way, our work bridges two fields of research developed so far independently, namely: the piezoelectricity of wurtzite semiconductors and the electrical control of magnetization in hybrid and composite magnetic structures containing piezoelectric components.

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