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Creating Wide Band Gap LEDs Without P-doping

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Wide band gap semiconductors like AlN typically cannot be efficiently p-doped: acceptor levels are far from the valence band-edge, preventing holes from activating. This means that pn-junctions cannot be created, and the semiconductor is less useful, a particular problem for deep Ultraviolet (UV) optoelectronics.

To create an LED or any optoelectronic light emitter, both electrons and holes are needed. We propose a novel heterostructure design concept to accomplish this *without* p-type doping. Holes can be created by impact ionization, but this requires a large voltage drop in a short distance, which can be achieved in a depletion region. Depletion regions require both a positive and negative charge to cause a voltage drop. Normally, p-dopants provide the negative charge. We propose to eliminate p-dopants and provide negative charge from both trapped electrons in quantum wells and heterojunction polarization charge. Using a heavily-doped n-region to complete the junction allows for impact ionization at moderate voltages (~15V in GaN). High energy electrons collide with bound electrons and create an electron-hole-pair. This creates an Avalanche LED as illustrated in Fig. 1. The polarization charge also creates a source barrier for electrons, limiting the number of electrons injected through the reverse biased depletion region (a key advantage over previous attempts [1]). In order to trap enough negative charge to form a depletion region multiple quantum wells are needed. In this work we simulate a GaN/InGaN structure to demonstrate the concept, but the device concept can be applied to any semiconductor heterojunction, and would be of course especially useful for wide band gap semiconductor heterojunction such as AlN/AlGaN where there is no effective p-dopant (We model GaN as the avalanche properties of AlN are not well known). It also works equally well for materials that cannot be n-doped. The simulations were done using Silvaco with a field dependent avalanche model, optical recombination, and tunneling through the quantum well barriers. Accounting for the electron temperature during avalanche should change the simulated efficiency slightly, but not the overall result.

In Fig. 2(a), the IV curves are shown for different numbers of quantum wells. Increasing the number of quantum wells increases the voltage that is dropped across the depletion region. This improves the gain of the avalanche region, reducing the number of electrons that pass through the device without creating a photon. This is reflected in the wall plug efficiency (power out/power in) plotted in Fig 2(b). Here we assume a light extraction efficiency of 100% to focus on the device physics. The lack of an absorbing p-contact allows for a high light extraction efficiency to be engineered. It is important to focus on the wall plug efficiency as around 15V are needed for each electron that creates a ~2.5 eV photon. This gives an efficiency limit of around 1%. This is comparable to deep UV LEDs (λ<250 nm) that currently have an EQE around 1-2% [2]. The efficiency is limited by the rate at which electrons escape from the quantum wells. They rapidly tunnel out, limiting the stored charge and therefore the effective p-type doping.

As seen in Fig 2(c) and 2(d), increasing the n-type doping does not increase the efficiency. This is because the effective depletion width is limited by the amount of charge trapped in the quantum wells. Reducing the quantum well depth reduces the voltage dropped across the depletion region and therefore the efficiency.

Fig. 3 shows that reducing the quantum well barrier thickness does not improve the efficiency as electrons tunnel out of the quantum wells faster, resulting in less stored charge. Consequently the maximum efficiency is achieved with 6 quantum wells instead of 4 as more wells are needed to trap the required charge. Impact ionization occurs throughout the depletion region, including both the quantum wells and the heavily doped GaN region as illustrated in Fig 4. The internal quantum efficiency is shown in Fig 5. It is limited to around 10% as a full avalanche breakdown was not achieved at the lower voltages due to the finite effective doping of the "p-type" region.

Overall we see that it is possible to use quantum wells to create depletion regions and impact ionization to generate holes.

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[1] AN Kovalev, et al. *Semiconductors* 32.1 54-57 (1998)

[2] H Hirayama, et al. *APE*, 3(3), 031002 (2010).

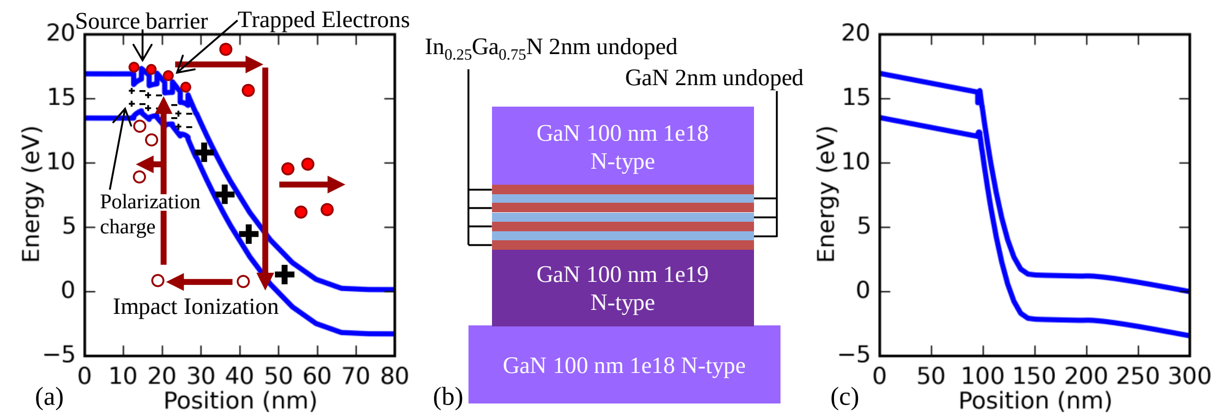

Fig.1: (a) The band diagram for the avalanche LED is shown. Four quantum wells are used to trap a large electron density to form the "p" side of a pn-junction. A heavy 1e19 n-type doping is used to minimize the depletion region thickness and maximize the electric field. This allows impact ionization to create holes to create an LED. (b) The physical structure is illustrated (c) Using a single quantum well does not trap enough charge to drop the entire applied voltage in the depletion region. Consequently some of the voltage is dropped on the contact regions.

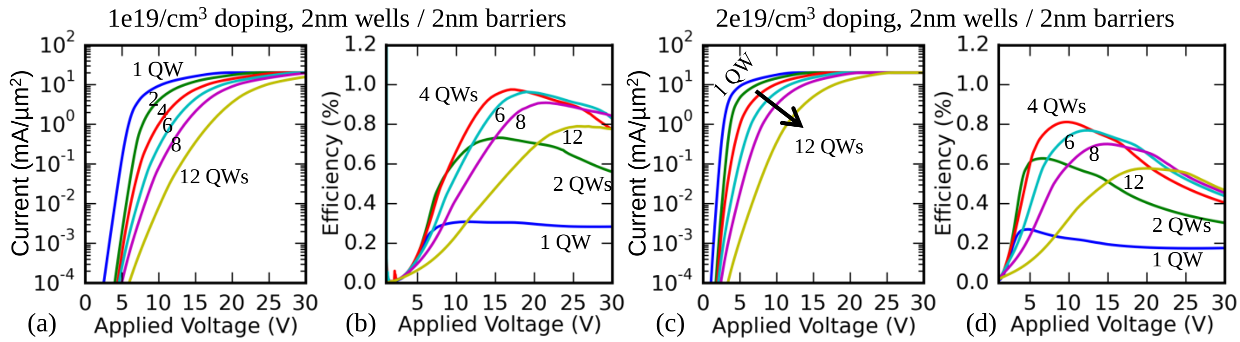

Fig. 2: (a) The turn on voltage increases as the number of quantum wells increases. The contact resistance (1e18 doped layers) causes the current to saturate. (b) The wall plug efficiency (assuming 100% light extraction) reaches a maximum of 1%. Increasing the number of quantum wells allows for more voltage across the depletion region, increasing the number of holes generated and therefore the efficiency. The current (c) and efficiency (d) are shown for an LED with 2e19/cm^3 donors in the depletion region. Increasing the doping does not improve the efficiency as the depletion width/electric field is limited by the quantum wells.

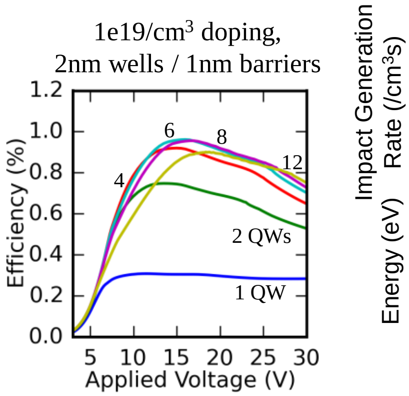

Fig. 3: Reducing the quantum well barrier thickness does not increase the efficiency as the thinner well region is offset by increased tunneling.

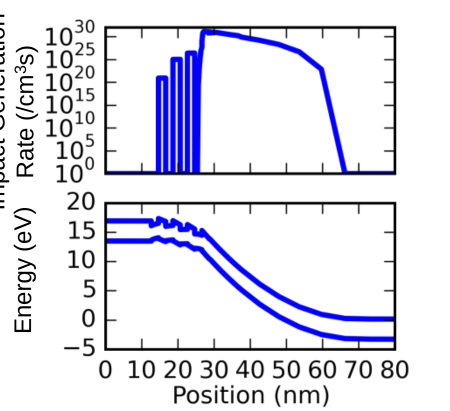

Fig 4: Impact ionization occurs throughout the depletion region

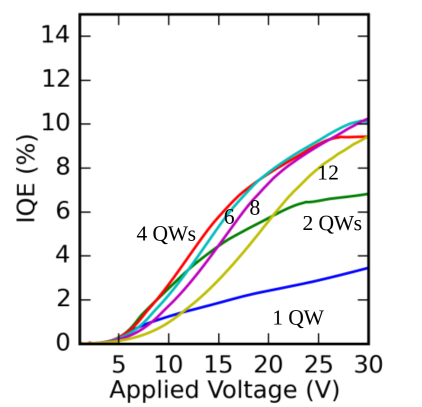

Fig. 5: The internal quantum efficiency for a 1e19/cm^3 doped LED approaches 10% as full avalanche breakdown is not reached at lower voltages.