Increasing the mobility of n^--GaN on silicon

A record room-temperature mobility of 1090cm^2/V-s has been achieved with a carrier concentration of ~$2x10^{16}/cm^3$.

Researchers based in China claim a record 1090cm^2/V-s mobility (μ) for lightly n-doped gallium nitride (n^--GaN) grown on silicon (Si) [Jianfei Shen et al, Appl. Phys. Lett., vol118, p222106, 2021]. The carrier concentration was ~$2x10^{16}/cm^3$. The previous mobility record was 720cm^2/V-s with $2x10^{16}/cm^3$ Si doping.

According to the team from Peking University, National Institute for Materials Science (NIMS), and Collaborative Innovation Center of Quantum Matter, a key factor in this achievement was the reduction of threading dislocations (TDs) in the n^--GaN. Further investigation suggested that the TDs attract acceptor-like carbon impurities from metal-organic chemical vapor deposition (MOCVD) — these carbon impurities can form charged Coulomb scattering centers.

Lightly n-doped GaN drift layers are a key component in vertical GaN based devices being developed for high-power and high-voltage systems for electric vehicles, power plants, data centers and consumer electronics. Such layers need to be relatively thick to reduce the peak electric field of the large potential drop. At the same time, the resistance needs to be as low as possible, requiring as high a mobility as possible.

Although higher mobilities have been achieved on other substrates, such as silicon carbide and freestanding gallium nitride (1470cm^2/V-s with $1.2x10^{15}/cm^3$ carrier concentration), manufacture on silicon substrates could significantly reduce costs, particularly if GaN electronics could be monolithically integrated with silicon CMOS circuitry.

The researchers grew their n^--GaN on p-type doped <111> Si. The team explored the use of dislocation filter (DF) layers of various thicknesses in the range 1–5μm, grown at 1020°C with an ammonia-rich 4534 V/III ratio.

The DF layer was grown on a buffer consisting of 300nm 1100°C aluminium nitride (AlN) nucleation and 400nm 1060°C $Al_{0.25}Ga_{0.75}N$ stress control layers to bridge the large ~17% lattice mismatch between GaN and silicon. The large mismatch is a key source of the higher TD density, relative to GaN grown on the much more expensive alternative substrates.

The top layer was 2μm n^--GaN with ~$3x10^{16}/cm^3$ silicon doping, grown at 1050°C temperature and 300mbar pressure.

The thicker 5μm DF layer resulted in a lower dislocation density in the top n^--GaN, according to x-ray diffraction analysis (Table 1). The results were consistent with inspection using transmission electron microscopy, which gave a value of $5.4x10^8/cm^2$ for sample C with a 5μm dislocation filter.

Secondary-ion mass spectroscopy (SIMS) showed that, along with reduced dislocations, the top n^--GaN layer also contained fewer carbon impurities.

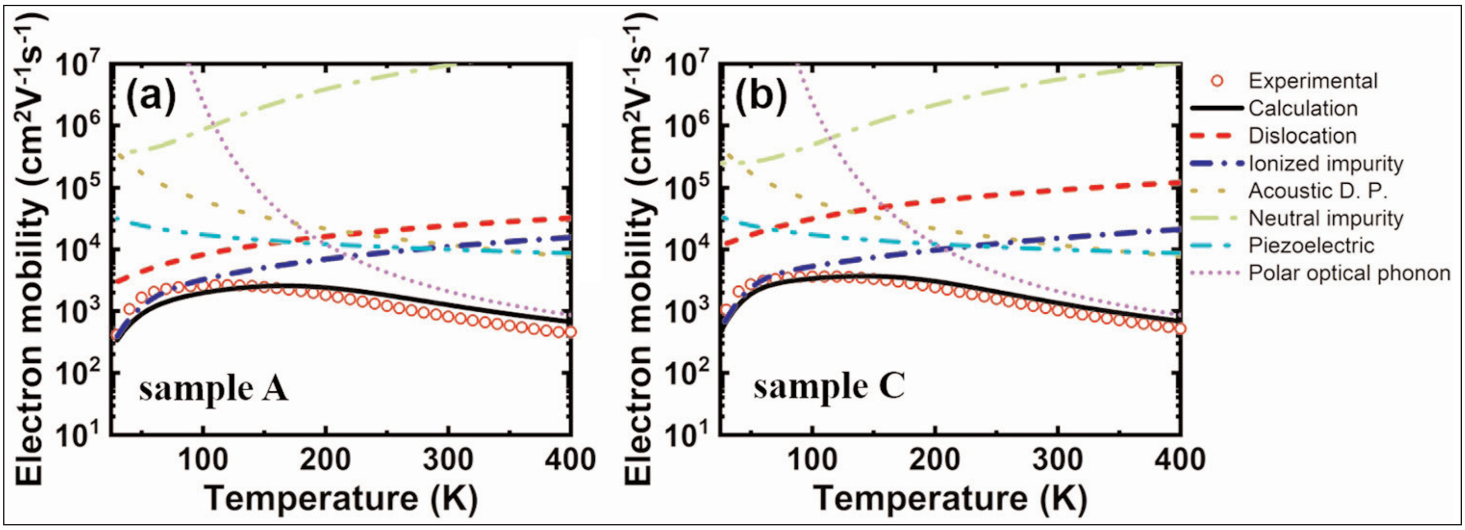

Figure 1. Temperature dependence of electron mobility of (a) sample A and (b) sample C. Calculated electron mobilities limited by individual scattering mechanisms also shown. Components combined according to Matthiessen's rule [$1/\mu = \Sigma 1/\mu_i$] to give calculated total.

The researchers found a linear relationship between the dislocation density and carbon concentration: “The linear dependence indicates that the incorporation of carbon impurity is closely associated with dislocation density. We suggest that the carbon impurities may segregate around the dislocations (carbon-decorated dislocations). Some previous experimental works have also shown evidence that dislocations behave as carbon-gathering centers.”

Table 1. Experimental comparison of three samples with different dislocation filter thickness.

Sample	DF thickness	TDD	Carbon concentration	μ at 300K
A	1μm	1.1x10^{9}/cm^{2}	1.7x10^{16}/cm^{3}	814cm^{2}/V-s
B	3μm	9.3x10^{8}/cm^{2}	1.3x10^{16}/cm^{3}	873cm^{2}/V-s
C	5μm	5.3x10^{8}/cm^{2}	4.6x10^{15}/cm^{3}	1090cm^{2}/V-s

Table 2. Properties determined through charge-balance considerations.

Sample	N_A	N_{DIS}	d_{DIS}
A	1.7x10^{16}/cm^{2}	9.6x10^{15}/cm^{3}	5.9Å
B	N/A	N/A	N/A
C	7.0x10^{15}/cm^{2}	N/A	N/A

The team believes that the carbon impurities around the dislocations may act as acceptor-like traps, which reduce electron carrier concentrations, along with impacting mobility through carrier scattering. These effects increase the resistance of drift layers in vertical devices. The improved material quality of the n^{-}-GaN in sample C resulted in a mobility of 1090cm^{2}/V-s, according to Hall measurements on Van der Pauw structures.

The researchers used temperature-dependent Hall measurements to disentangle the various theoretical contributions to the mobility (Figure 1). For sample A (1μm DF), the peak mobility was 2620cm^{2}/V-s at 120K. The sample C peak was 3628cm^{2}/V-s at 110K. According to the researchers, the peak occurring at lower temperature indicates a lower compensation trap (N_A) concentration.

Despite the higher dislocation density compared with material grown on pure GaN substrates, the contribution of dislocation scattering in sample C was found to be comparable. The researchers suggest that the key factor is whether the dislocations are charged or not. If the dislocation has trapped carbon atoms which in turn have trapped electrons, the charges produce Coulomb scattering.

Further analysis was used to extract information from the temperature dependence of the Hall carrier concentration (Table 2). The team estimated acceptor concentrations ([N_A]), concentrations of TD-related acceptor states ([N_{DIS}]), and the distance between occupied acceptor-like trap states along a TD (d_{DIS}), using charge balance equations. The last value, d_{DIS}, was found to be of the order of the lattice parameter in the vertical c-direction of the GaN crystal lattice. “That means an acceptor-like trap state (one carbon atom decorated near a dislocation) was estimated to exist at every c-lattice spacing along a TD,” the researchers comment. ■

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Author: Mike Cooke