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Resonant-tunneling electron emitter in an AlN/GaN system

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An AlN/GaN multiple-barrier resonant-tunneling electron emitter is proposed in this letter, utilizing polarization fields in the AlN/GaN heterostructure. The resonant-tunneling voltage is extremely high, compared with usual resonant-tunneling devices, due to the polarization field in the heterostructure, and this high resonant voltage enables practical use of the devices. Selective and high-density electron emission is to be expected through the resonant-tunneling layer and GaN surface accelerating layer. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1922081]

A variety of electron field emitters using materials such as carbon nanotubes, silicon, and diamond have been studied for application in flat-panel displays.[1–3] Nitride semiconductors and quantum wells are also useful for their application in electron emitters. InGaN/GaN and GaN/AlN heterostructure field emitters have indicated a strong decrease in the electron affinity on the cesiated surface, owing to the quantum-size effect and strong polarization at the nitride surface.[4,5] Negative electron affinity (NEA) has been reported for cesiated AlN and effective photoelectron emission has also been reported for *p*-type GaN.[6,7] Figure 1 shows band structures of a nitride field emitter and a photoelectron emitter. A GaN/AlGaN/GaN or InGaN/GaN quantum-well structure grown in the +*C* direction has strong polarization field at the surface as shown in Fig. 1(a), and the electron affinity is effectively decreased by the quantum-size effect in the triangular surface potential. Thus, these structures are useful as field emitters with small electron affinity. Cesiated *p*-type GaN exhibits an effective NEA, as shown in Fig. 1(b), and a photoemission efficiency of around 20% has been reported. Electrons created by the incident photon are accelerated to the surface by the surface electric field, and some of the electrons are ballistically emitted into the vacuum. Electrons created very near the surface do not have sufficient kinetic energy to exceed the vacuum level, and some of the electrons created far inside the surface recombine with holes before being accelerated by the surface electric fields. In this letter, an electron emitter is proposed, utilizing the strong polarization field in an AlN/GaN heterojunction to enable both ballistic electron emission and electron injection into surface accelerating layer through a resonant-tunneling multiple quantum well (MQW). In the AlN/GaN quantum well system, AlN and GaN layers have huge polarization fields due to the spontaneous and piezo polarizations. The polarization field can be effectively used to inject conduction electrons into higher levels. The authors recently proposed mid- and near-infrared quantum-cascade structures where electrons are injected to higher subbands through a few atomic layers of AlN, or through simple resonant tunneling in AlN/GaN layers.[8,9] The resonant-tunneling voltage of the AlN/GaN MQW is governed mainly by the polarization fields in the quantum well, and possesses a large value.[9,10] The large tunneling voltage would be also useful for application in electron emitters because the electric field just beneath the semiconductor surface is controlled by the polarization field, as is shown subsequently.

Figure 2 shows the schematic device structure of the AlN/GaN resonant-tunneling electron emitter. The band structures of the emitter with and without bias voltage are shown in Fig. 3. The emitter is grown in the +*C* direction, and the device is composed of an $(\mathrm{AlN})_{n1}/(\mathrm{GaN})_{n2}$ ($n_1 \sim 5$, $n_2 \sim 20$ in atomic layers) MQW resonant-tunneling layer on an *n*-type GaN electron-source layer, with an n^--GaN accelerating layer with a thickness of 50 nm at the emission window. The GaN accelerating layer below the surface electrode (~100 nm) is thicker than that at the emission window. The carrier concentration at the n^--GaN accelerating layer is less than $1 \times 10^{18}\ \mathrm{cm}^{-3}$, while resistivity of the surface of the emitter window is kept low, either by highly doping the GaN surface or by a thin deposition of metal. Since the AlN layer in the MQW is very thin, the AlN is completely strained and the lattice constant in the layer plane matches that of the GaN. As a result, the layer exhibits a high piezoelectric field E_z of 0.56 V/nm, as given by the equation[11]

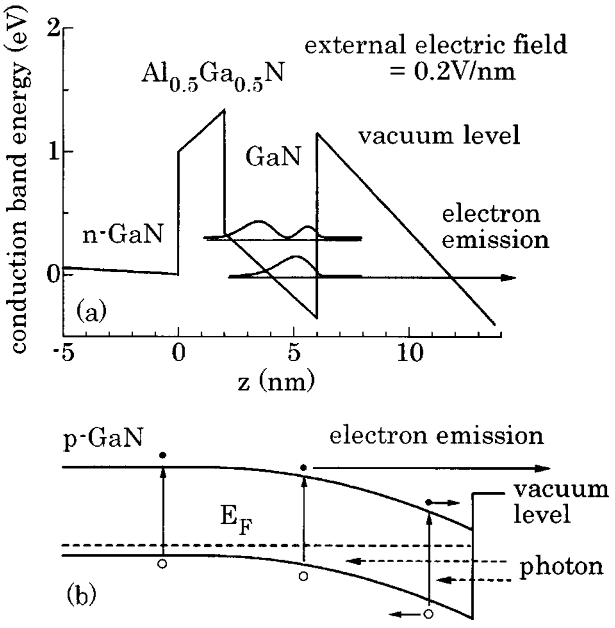

FIG. 1. Energy band structures of (a) *n*-GaN/AlGaN/GaN quantum well field emitter, and (b) *p*-GaN photoelectron emitter.

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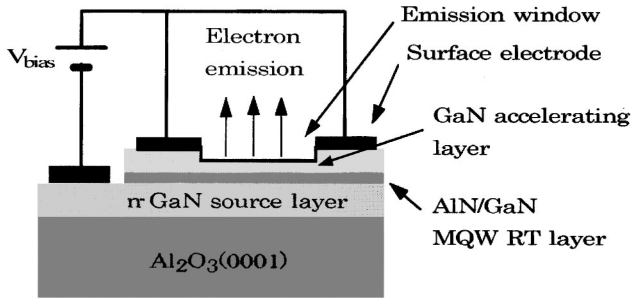

FIG. 2. Schematic device structure of an AlN/GaN resonant-tunneling electron emitter. The AlN/GaN resonant-tunneling layer is composed of an $(AlN)_3/[(GaN)_{20}/(AlN)_5]_4$ structure, with the thicknesses of the surface GaN accelerating layer being 50 nm at the emission window and 100 nm below the electrode.

$$E_z = -p_z/\varepsilon = -[e_{31}(e_{xx}+e_{yy}) + e_{33}e_{zz}]/\varepsilon \tag{1}$$

$$=2(e_{33}C_{13}/C_{33} - e_{31})e_{\|}/\varepsilon,$$

where p_z is dipole moment due to the piezo effect, ε is dielectric constant of the material, e_{31} and e_{33} are piezo coefficients, and C_{13} and C_{33} are the elastic stiffness constants of the material. AlN also exhibits a high spontaneous polarization due to the deviation from a regular tetrahedral shape. The polarization field is estimated as high as 0.24 V/nm from consideration of the deviation from the regular tetrahedral shape. Thus total polarization fields E_p in the AlN layer reaches a level of 0.8 V/nm, and the conduction-band edge of the AlN rises to the surface (+C direction), as shown in the Fig. 3(a). On the other hand, electron transfer occurs from the surface of GaN accelerating layer to the interface between the MQW and the GaN electron-source layer, so that the Fermi level becomes constant in all regions, and the electric fields in the AlN layer and GaN accelerating layer may be calculated as follows:

$$E_{\mathrm{AlN}} = E_p - \sigma_c/\varepsilon_{\mathrm{AlN}}, \tag{2}$$

$$E_{\mathrm{GaN}} = -\sigma_c/\varepsilon_{\mathrm{GaN}}, \tag{3}$$

where σ_c is the conduction charge density transferred from the interface of the GaN source layer and the MQW layer to the surface of the GaN accelerating layer, and is given by

$$\sigma_c = E_p L_{\mathrm{AlN}}/(L_{\mathrm{AlN}}/\varepsilon_{\mathrm{AlN}} + L_{\mathrm{GaN}}/\varepsilon_{\mathrm{GaN}}), \tag{4}$$

where L_{AlN} and L_{GaN} are the thicknesses of total AlN layer in the MQW layer and the total GaN layer in the MQW and GaN accelerating layer, respectively. The AlN/GaN MQW and GaN accelerating layers are thus depleted, as shown in Fig. 3(a). When an external voltage is applied to the surface electrode, the charge density σ_c increases, and electric field at the GaN accelerating layer increases as shown in Fig. 3(b). The resonant condition is simply calculated as follows:

$$E_p W_{\mathrm{AlN}} = \sigma_c'[(W_{\mathrm{AlN}}/\varepsilon_{\mathrm{AlN}}) + (W_{\mathrm{GaN}}/\varepsilon_{\mathrm{GaN}})], \tag{5}$$

where σ_c' is the charge at the surface of the GaN accelerating layer after bias, and W_{AlN} and W_{GaN} are thicknesses of the AlN and the GaN layers in the MQW, respectively. The bias voltage required for resonant-tunneling is obtained from Eq. (5) and is given by

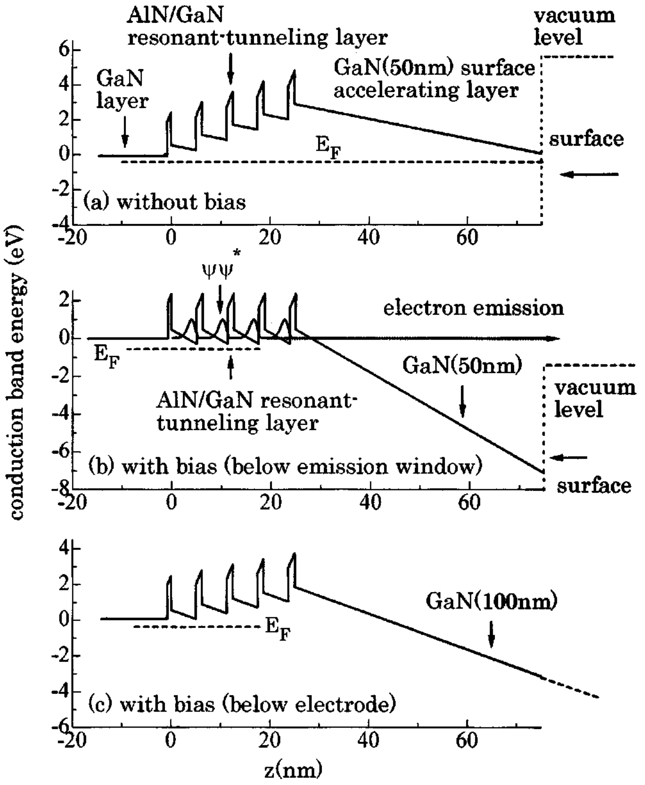

FIG. 3. Conduction band diagram of resonant-tunneling electron emitter (a) without bias, (b) with bias at the emission window, and (c) with bias below the contact electrode.

$$V_{\mathrm{bias}} = E_p\{W_{\mathrm{AlN}}[(L_{\mathrm{AlN}}/\varepsilon_{\mathrm{AlN}}) + (L_{\mathrm{GaN}}/\varepsilon_{\mathrm{GaN}})]/[(W_{\mathrm{AlN}}/\varepsilon_{\mathrm{AlN}}) + (W_{\mathrm{GaN}}/\varepsilon_{\mathrm{GaN}})] - L_{\mathrm{AlN}}\}, \tag{6}$$

The bias voltage V_{bias} needed to satisfy the resonant-tunneling condition is calculated to be as high as 7 V with these thickness conditions. Thus, accelerated electrons possessing energy higher than vacuum level are emitted from the emission window. In the $(AlN)_5/(GaN)_{20}$ MQW resonant-tunneling layer, the quantum level is calculated as 0.33 eV from the right bottom of the GaN well by the envelope-function approximation taking into account the polarization fields.[12] As a result, the thickness of the first AlN layer in the MQW was designed to be three atomic layers in thickness so that the conduction-band edge of GaN source layer has almost the same energy as the quantum level in the MQW layer in resonant-tunneling condition. The tunneling current was estimated to be as high as 3 kA/cm^2 by Wentzel-Kramers-Brillouin approximation if it is assumed that the carrier concentration at the interface between GaN electron-source and MQW layers is 1×10^{18} cm^{-3}.

In a practical device, the loss current or current flow at the surface electrode should be sufficiently low, and the electron affinity of the GaN surface layer should be also lower than the band gap of accelerating layer. If the kinetic energy of the conduction electron is higher than the band gap, impact ionization becomes significant and electron-emission efficiency decreases. Thus, a surface treatment would be necessary to decrease the electron affinity of the GaN surface. The former problem could be overcome by using a thicker GaN surface layer below the electrode than that at the emission window, as shown in Fig. 2. The resonant-tunneling voltage given by Eq. (6) depends on the thickness of GaN accelerating layer, and the resonant-tunneling voltage below the electrode becomes greater than that at the emission window. Thus, selective electron emission is possible merely by varying the thickness of the GaN accelerating layer, as shown in Figs. 3(b) and 3(c). Efficiency of electron emission depends on the high-field relaxation time of the conduction electrons, but detailed experimental data on GaN have not been reported. However, an efficiency comparable to or greater than a *p*-GaN photoelectron emitter is expected for the well-engineered resonant-tunneling device, considering the difference in the operation mechanism between the resonant-tunneling emitter and photoelectron emitter.

In summary, an AlN/GaN surface-emitting resonant-tunneling electron emitter has been proposed, utilizing a high polarization field in the AlN/GaN heterostructure system. The resonant condition depends mainly on the polarization field, and the device with a high resonant voltage can be designed by adjusting the polarization parameters. High-density electron emission is expected to result from the resonant-tunneling through the multiple AlN layers, and selective electron emission from the emission window is expected with an appropriate design of the GaN surface accelerating layer.

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