Chapter 9 Gate Controlled ZnO Nanowires Triode Field Emission Devices (ZnO NWs TFED)

9.0 Preface

Metal oxide nanowires (NWs) such as ZnO, In_2O_3, and SnO_2 etc. have well field emission characteristics because of their better geometry for high aspect ratio and all have beyond 3.0 eV wide band gap level. Gated controlled field emission devices have great promise for a number of applications. The gated controlled ZnO NWs field emission device which used the lift-off fabricated process to synthesize side gate type controlled effectively focus the turn-on electron beams and switch the drain current (I_d) at threshold voltage (V_T) at ~ 35 V. In the meantime, the current density can achieves ~1 mA/cm^2 is similar to CNTs field emission level which could potential to field emission display (FED) devices. Furthermore, when the V_g is equal to 0 V, the turn-on electric field (E_{to}) for ZnO NWs is ~0.8 V/μm and the field enhancement factor, β is ~ 7073; then V_g is applied equal to 10, 20, 30, and 40 V, the E_{to} are low to ~0.8-0.6 V/μm and β value are also increase to ~7600-17800. That means the gate voltage (V_g) added continuously which can help lower the turn-on electric field because of the local electric field (E_{local}) generated an extra force prompt the more electrons can speedy and emission from the ZnO NWs. Besides, the g_m value is can approach to 3.88×10^{-4} S while the V_g is applied to 44.5 V. To provide a controllable electron beams from metal oxide NWs field emission device, we built a ZnO NWs array of side-gate controlled which fabricated using only one critical mask lift-off process. The devices have well controlled behavior and exhibit better Fowler-Nordheim (F-N) characteristic. The gated ZnO NWs array have good opportunity to apply to FED devices and also integrated semiconductor industry in the future.

9.1 Introduction

Recently, a new class of triode structure for field emitting devices had been suggested,[305-307] the so-called side-gate-type triode field emitters where the gate electrodes are located around the cathode electrodes with a gate dielectric oxide or isolation layers. In the previous earlier reports,[308-310] there are some triode type field emission devices were fabricated by a series of carbon such as carbon nanotubes (CNTs) or diamond-like carbon (DLC) which have good field emission properties and good controlled ability. Besides the series of carbon, some II-VI semiconductor nanostructure likes nanowires, nanobelts or nano-tetrapods are investigated in these field emission characteristics[311-313]. The material, ZnO is a well II-VI semiconductor which has ~60 meV excited energy and ~3.47 eV wide energy band gap that has attractive potential for nano-electronics or nano-optical applications. Many of ZnO nanowires (ZnO NWs) fabrication methods or material properties are presented for previous studies.[314-315] To be aimed at the characteristics of field emission of ZnO NWs, we had report some results to study the efforts in turn-on electric field, current density or series resistance while added less dopant or controlled the carrier gas flow in the fabrication of the ZnO NWs.[315-317] In this study, the one-step lift-off process was introduced to fabricate a side-gate-type controlled ZnO NWs field emission devices. The gate dielectric isolating layer was deposited by rf-sputter using ZnO to generate an extra focusing electric field while applied gate voltage (V_g). The emitter structure is used for the ZnO NWs that was obtained by a vapor-liquid-solid (VLS) process.

9.2 Fabricated Process and Structure

The gated controlled ZnO NWs field emission devices were fabricated through a number of processes which was shown in Fig. 1. The 200 nm dry silicon dioxide (SiO_2) was thermally grown on p-type Si(100) substrate at ~1050 ^{o}C. This structure is present to a well gate dielectric layer which using to control the properties of field emission of the ZnO NWs. Then the bottom electrode Pt was deposited by rf-sputtering under 60 W, 20 mTorr Ar ambient and was used post annealing (350 ^{o}C, N_2 purged atmosphere) process. The 0.7 nm ultra thin (002) ZnO buffer layer was using rf-sputter deposition under 5 mtorr Ar gas atmosphere on the Pt/SiO_2/Si substrate which helps the ZnO NWs synthesized vertically[15] which could effect improve the ability of field emission. After lithography process, the gate electrode to whom selected for it well conductance, Pt, was deposited at the same recipe and annealed at 350 ^{o}C for a while. Finally, the 0.6 nm ultra thin Au catalyst was using rf-sputter to deposited in the patterns which the width is ~50 μm and using lift-off process to remove photo resistance. After these pre-prepared triode structure deposited process, the ZnO NWs was synthesized by vapor-liquid-solid (VLS) process using horizontal speedy thermal furnace at ~900 ^{o}C for 30 min. to finish this side gate controlled ZnO NWs field emission devices.

The field emission properties of the gated controlled ZnO NWs field emission devices were characterized in a high vacuum measurement chamber with a base pressure of 5.0×10^{-8} torr. The detail setup for measurement was

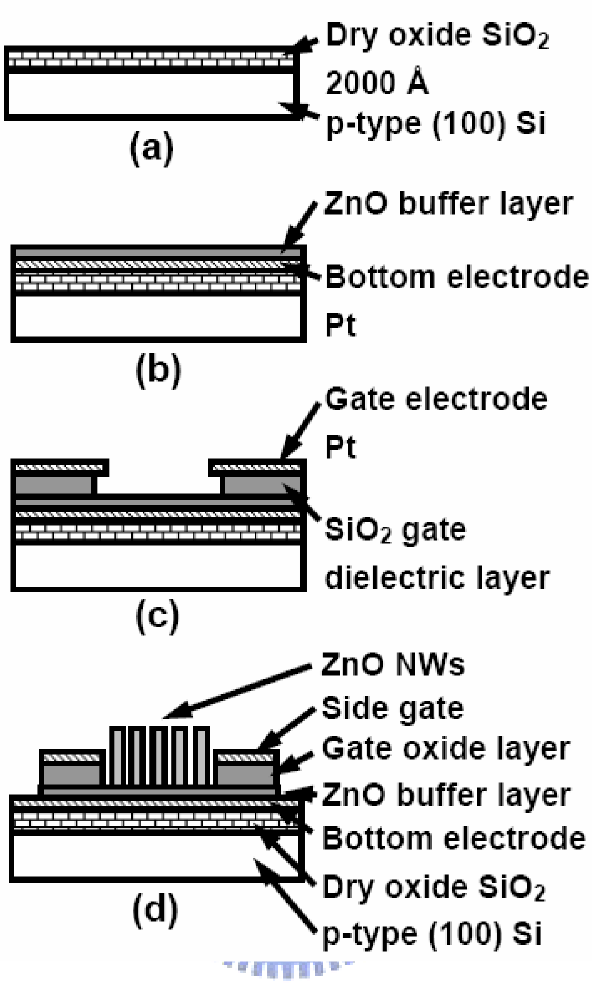

Figure 7.1 The fabrication process for the triode structure for gate controlled ZnO NWs field emission devices.

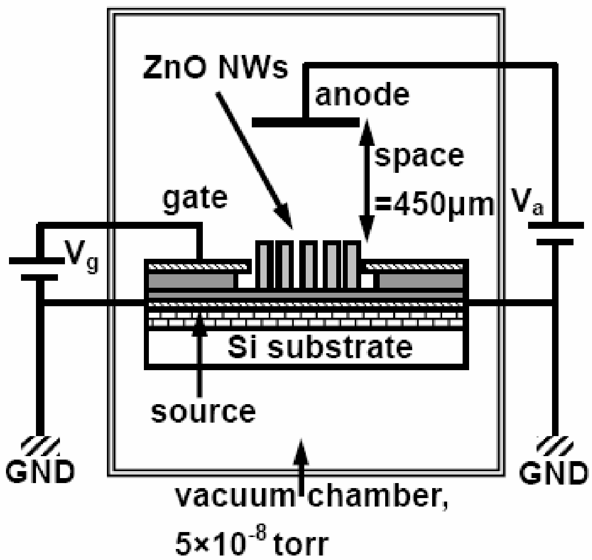

Figure 7.2 Schematic diagram of a high vacuum chamber system for field emission measurement.

shown in Fig. 2. The vertically field emission transistor (FET) setup was measured the drain current (I_d) function of the gate voltage (V_g). An anode was made by Cu and located 450 μm above the ZnO NWs. The controllable V_g is set up by the Agilent® 3645A DC power supply which also offer ~60 V DC controlled by GPIB interface. The anode current was measured as a function of controlled gate extra voltage and anode voltage, using Keithley® 237 high voltage source unit and Pentium® PC supported.

9.3 Results and Discussion

9.3.1 The Characteristics of Material Analysis of Gate Controlled ZnO NWs TFED

Figures 7.3 show the field emission scanning electron microscopy (FE-SEM) images of the gated controlled ZnO NWs field emission devices. The geometry of the device is shown in Fig. 7.3(a), the width of square ZnO NWs is ~50 μm and the space of each square pattern is 150 μm. For this geometry relationship, the half pitch of the experimental prototype is ~100 μm. Although the pitch width is wider than general IC technology, the wider pitch also offer better distinguished ability to judge the gate controlled field emission characteristics of each TFED ZnO NWs device. In Fig. 7.3(b), the detail nanostructure is shown for ZnO NWs. Resulting the ZnO buffer layer which reduce the mismatch between ZnO NWs and Si substrate that report elsewhere, the (002) ZnO NWs are all vertically growth inner the pattern and have uniform geometry that will help to enhance the properties of field emission. The VLS process synthesized ZnO NWs are ~4 μm length and ~50 nm width which have well crystalinity through high resolution transmission electron microscopy (HR-TEM) and X-ray diffraction analysis (XRD) that show in the later section. The tips of the ZnO NWs have no remained Au catalyst which means that we introduced the two-step VLS process is helpful to

According the XRD analysis shows in Fig. 7.4(a), The ZnO NWs have prefer orientation on (002) direction. There are some weak peak such as (100) and (110) are found which result in the lattice mismatch or harmfully local growth controlled through the VLS process. The full width half width (FWHM) of (002) ZnO NWs is ~0.145^o which means the fabrication process is offer good condition for the ZnO NWs field emission devices to obtain almost

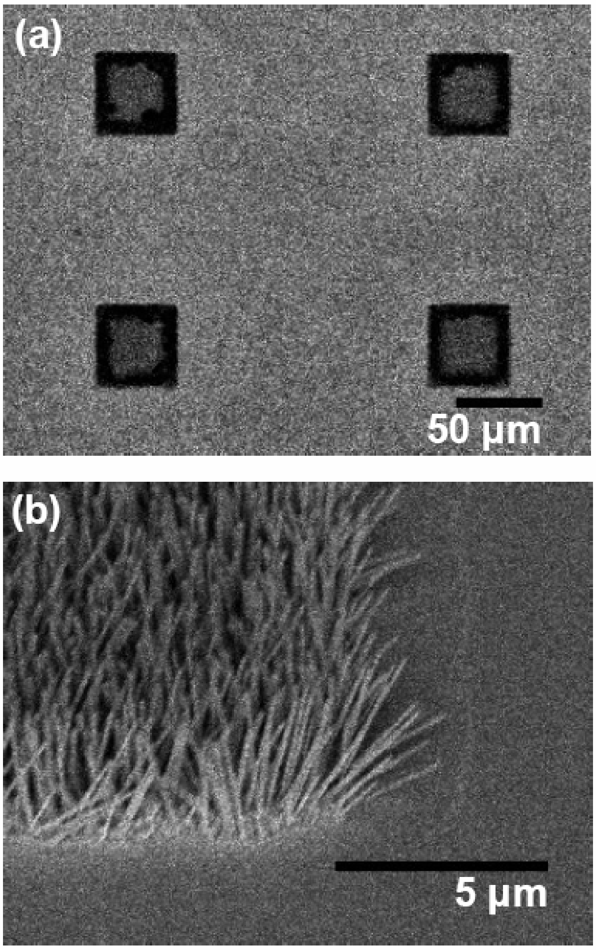

Figure 7.3 SEM images of ZnO NWs synthesized on the emitter region of the triode. (a) a entirety image for four triode devices of the ZnO NWs and (b) vertically growth ZnO NWs on the emitter region.

vertically growth ZnO NWs. In Fig. 7.4(b), the HR-TEM image is indicates that the good crystalline of the ZnO NWs.

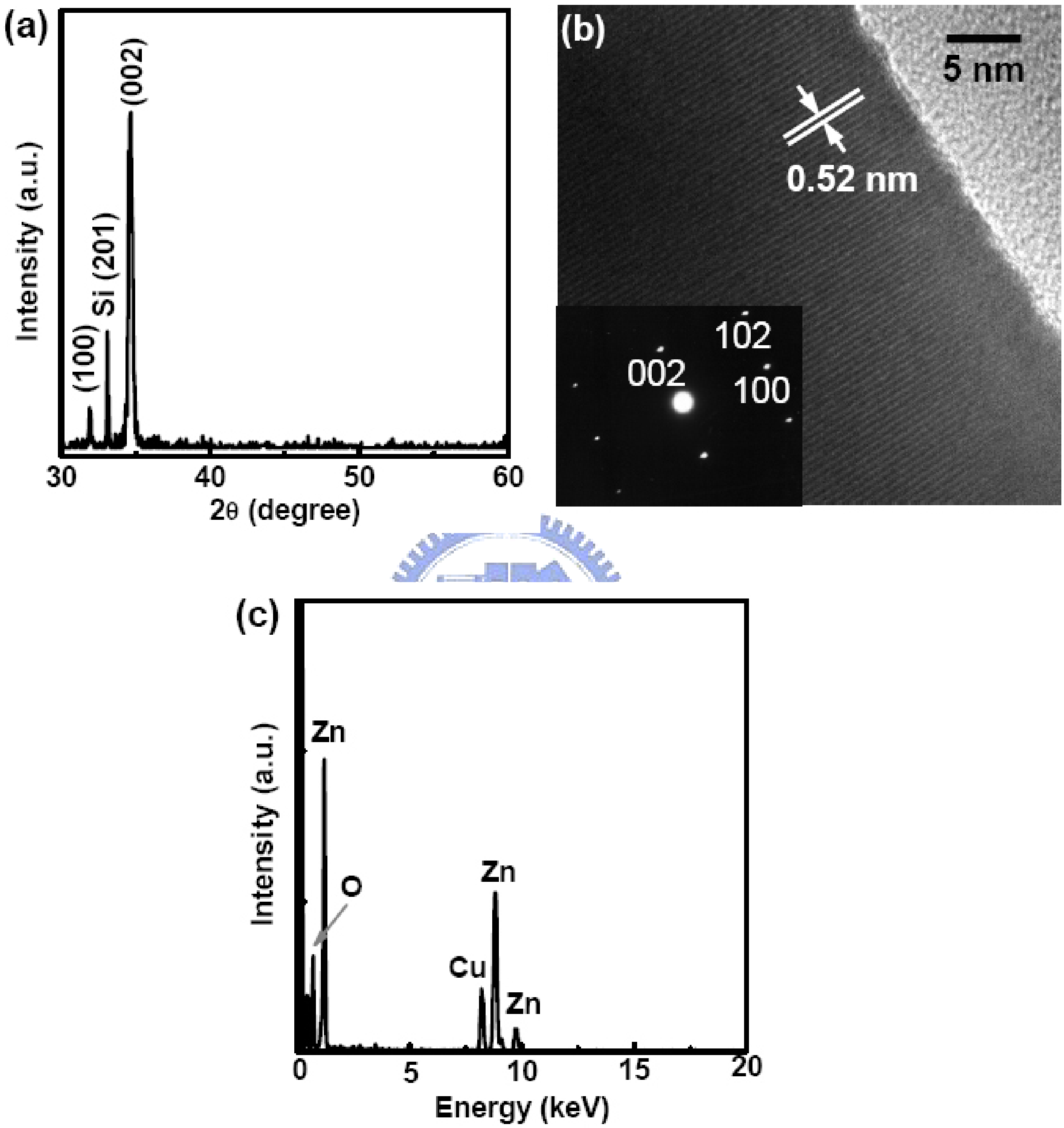

Figure 7.4 The XRD pattern and HR-TEM images of the ZnO NWs. (a) the XRD pattern presents the (002) prefer orientation ZnO NWs, (b) HR-TEM image indicates the lattice fringes and SAED image on the inset, and (c) the EDS patterns for chemical composition of the ZnO NWs.

The clear lattice fringes imply the d-spacing of (002) c-axis is ~0.52 nm NWs is smooth and fewer defects have. The inset of Fig. 4(b) shows the selective area electron diffraction (SAED) pattern along the (010) zone axis; which consisting the International Centre for Diffraction Data (ICDD-2000) data base #80-0075 of ZnO. Through this image shows the side wall of ZnO the indexed spots present the well crystalline of the ZnO NWs using the VLS process. The Fig. 4(c) is the electron (EDS) result which can indicates the chemical composition of ZnO NWs. The Zn and O mole ratio is very close to 50/50 also demonstrated the less impurities existence into the ZnO NWs. In the summary, the VLS process offer better synthesis control and easily fabricated method for the gate controlled ZnO NWs field emission devices.

9.3.2 The Field Emission Properties of Gate Controlled ZnO NWs TFED

Figures 5 are typical field emission properties of the gated controlled ZnO NWs field emission devices. In Fig. 5(a), the turn-on electric field of the gated controlled ZnO NWs field emission device is function of the gate voltage (V_g) which applies to 10, 20, 30 and 40 V. The turn-on electric field can decrease from 0.95 to 0.63 V/μm that is result in the side gate offers extra electric field while apply plus V_g. The extra electric field could be help more electrons excited from the tips of ZnO NWs that increases turn-on current density and decreases the turn-on electric field. The field emission characteristic that is follows the Fowler-Nordheim (F-N) equation which can presents as the Eqn. 1.

$$J = \frac{A\beta^2 E^2}{\phi} \exp\left(\frac{-B\phi^{3/2}}{\beta E}\right), \qquad (1)$$

Where J is the current density, E the applied field, ϕ the work function of the emitter, β the field enhancement, A = 1.56×10^{-10} (AV^{-2} eV) and B = 6.83× 103 (VeV$^{-3/2}$ μm^{-1}). The F-N plot is shown in the Fig. 5(b) comparing the effort of V_g for turn-on electric properties of the gated controlled ZnO NWs field emission devices. The total electric field (E_{total}) which can separate one is gate induced electric field (E_{gate}) and another is source-anode electric field (E_a). The

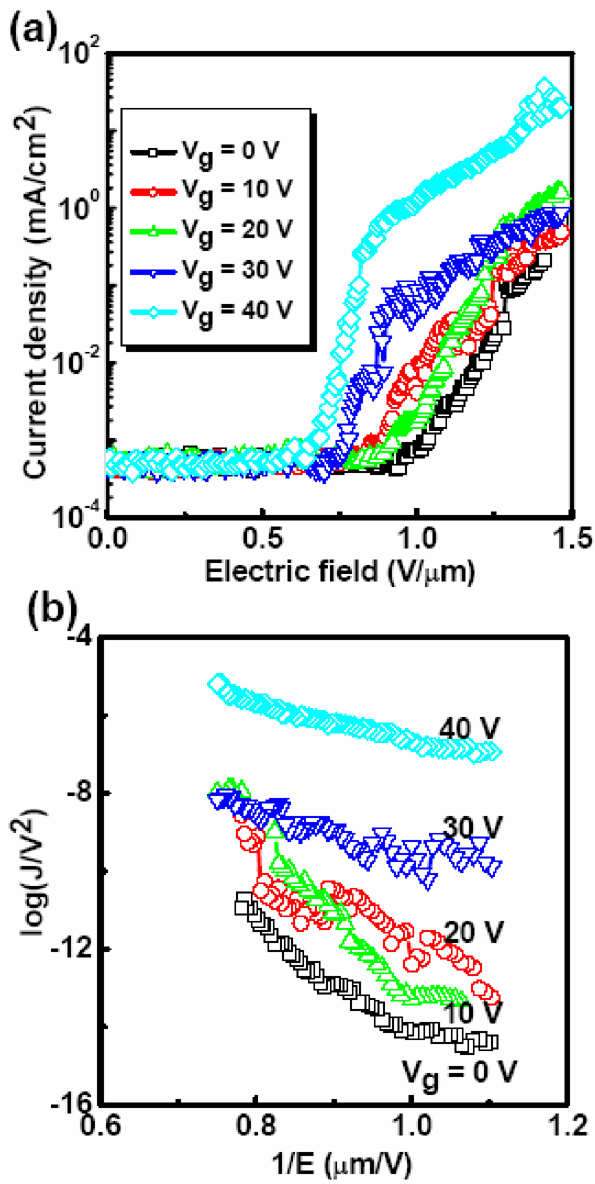

Figure 7.5 The field emission properties for (a) different gate voltage, V_g v.s turn-on electric field and (b) F-N plot for different V_g field emission characteristic.

slope form each line on the F-N plot are getting smaller that indicate the field emission enhancement factor, β becomes to large which can see in the Table 1. The variation of β is between ~7073 to ~18700 according apply V_g is 0 to 40 V that means the side gate will effectively switch this field emission device and the optimization condition is that V_g is equal to ~37 V. About the gated controlled properties of the ZnO NWs field emission devices will present later.

The side gate in this field emission device plays a controlled terminal which applies the voltage to introduce extra electric field to focus or speed up a number of electrons was emitted from the ZnO NWs array. The different electric field and turn-on current density are function of the gate voltage (V_g) which shows in Fig. 6(b). While under the different turn-on electric field, the drain current (I_d)-gate voltage (V_g) curves contain three regimes of interest, as shown in Fig. 6(a) and (b). The regime of V_g is from 5 to 35 V that call gate leakage regime which causes I_d decreased function of V_g increased because of the some leakage mechanism from space-charge-limited current flow, a combination of space-charge-limited current via filled trap states in the depleted channel and ohmic conduction through the substrate, Schottky gate diode reverse leakage current and a parasitic bipolar transistor action at large drain bias values. When V_g is beyond 35 V but not exceed 48 V, the I_d increase very speedy which called field emission excited regime cause by the potential was decreased result enough gate voltage. On the other hands, the V_g leads the energy barrier become more smooth and lower than no V_g applied which let more electrons can easily tunneling this barrier escaping from the tips of ZnO NWs to anode. At least, V_g is equal to ~50 V that leads I_d going through into the saturation regime and the saturation turn-on current is reach to ~1 mA/cm^2. Within this normal regime of channel gating above threshold, the carrier density or means doping profile is an important role which offers the current magnitude. In the Fig. 6(b), from the I_d-V_g plot analysis with different turn-on electric field, the better stability emission current was controlled under a higher V_g (V_g > 35 V) and must be in the steadier turn-on electric field. (ex. E_{total} > 1.61 V/μm)

Form the linearity of the F-N plot [ln(I/E^2) v.s. 1/E] of the electron emission properties from the triode structure is function of V_g which is shown in Fig. 6(c). The characteristic knee of each different applied electric field which indicated in the Fig. 6(c) presents the space charges variation which located in high electric field in the ZnO NWs. In the low applied electric field, (below 1.61 V/μm) the linearity F-N plot are obey the F-N eqn. which means the space charges effect is less than F-N tunneling. On the other hands, the electric field is higher beyond 1.61 V/μm that cause field emission current decrease speedy which have obvious characteristic knee. The effects of space charge and of the series resistance are apparent from these curves, which are applicable to a large class of materials such as NWs. Resulting in the space charge effect, we need to applied V_g to high voltage (V_g > 20 V) which could effectively decreases the induced space charges and limits the space charges emission at the same time. While the space charges were limited by V_g, the field emission of ZnO NWs can obey the F-N theory and have better controlled properties.

To study the transconductance, g_m of anode current (I_d) and gate voltage (V_g) which present in Fig. 6(d). Each g_m curve for different turn-on electric field just has one maximum value which means the optimized value for control the I_d current for applied V_g. In our study, under larger operating electric field beyond ~1.61 V/μm, V_g can induce higher focusing electric field which contributory to generate lower g_m (3.88×10^{-4} S) at small V_g equal to 44.5 V. But if the applied electric field is lower to ~1.45 V/μm the controlled V_g is equal to ~48 V corresponding to the maximum g_m (3.92×10^{-4} S).Under the different applied electric field, that is, while the applied electric field also call applied

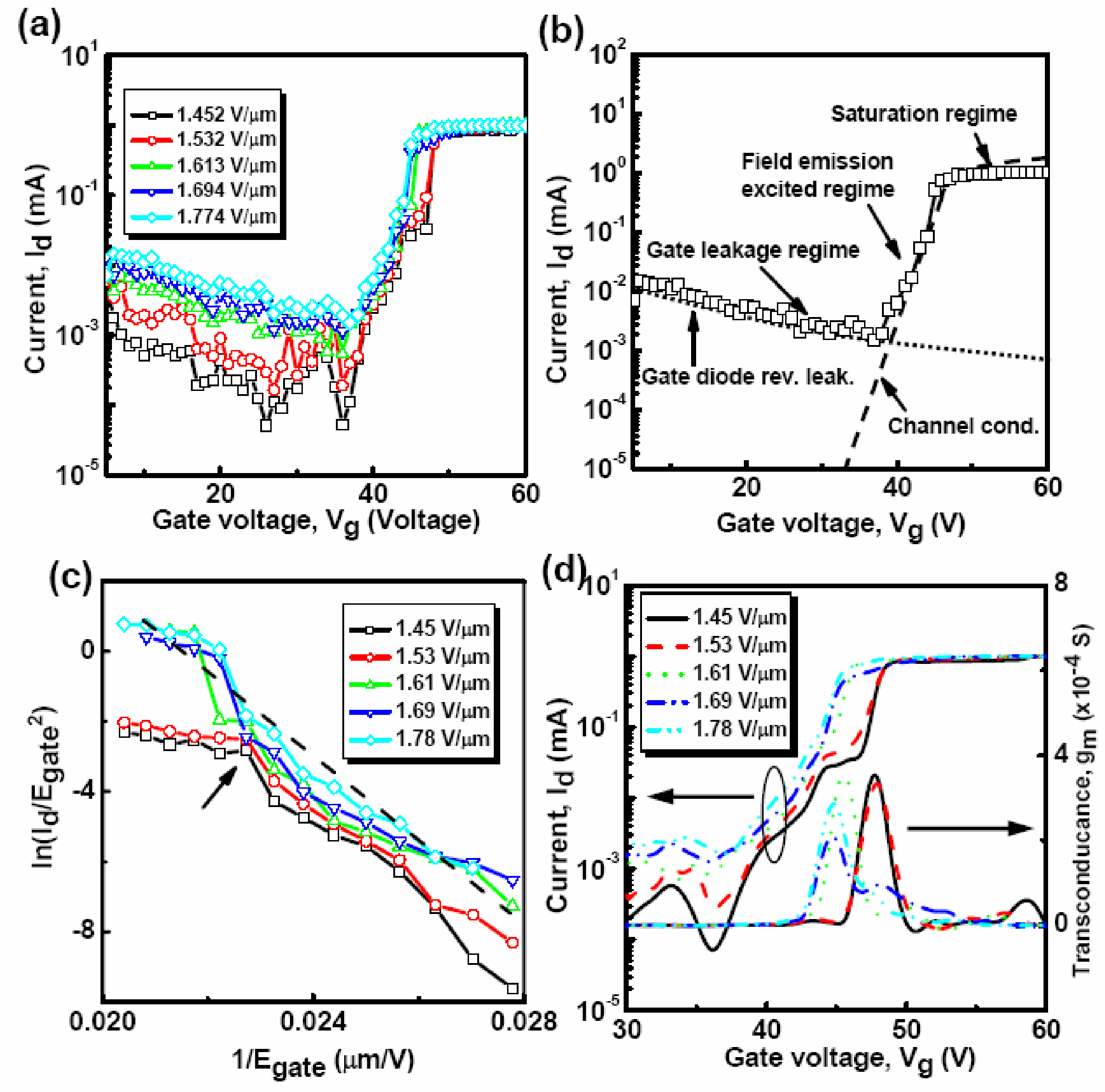

Figure 7.6 (a) The drain current, I_d function of different gate voltage, V_g characteristic curves, (b) I_d v.s. V_g. for gate controlled ZnO NWs field emission device, (c) the F-N plot for different V_g v.s emission current, and (d) transconducance, g_m v.s. different turn-on electric field.

emission devices have better control ability at higher electric field from V_g voltage (V_{ds}) which means the voltage drop from anode to cathode is getting increase the maximum of g_m is shift to lower V_g range which means the ZnO NWs can emitted more stable current density under the high V_{ds} and lower V_g. The side gate controlled ZnO NWs fabricated showed emission modulation by control of the gate voltage. Therefore, the side gate controlled ZnO NWs field which also let I_d become more stable.

Table 9.1 The relationships of gate voltage, (V_g), turn-on electric field, (E_{to}) and the field emission enhancement factor, β of the gated controlled ZnO NWs field emission devices.

V_g (V)	E_{to} (V/μm)	$\beta_{emitter}$
0	0.92	7051
10	0.89	7323
20	0.84	7601
30	0.73	16360
40	0.58	17838

9.4 Summary

In summary, the gate controlled ZnO NWs field emission devices have been successfully fabricated by a simple lift-off process. About the physical and chemical properties of the VLS process fabricated ZnO NWs which have well crystalline and composition that can investigate by TEM, XRD and EDS analysis. The field emission characteristics are improved while applied the gate voltage (V_g). Under the V_g is equal to ~35 V, the turn-on electric field is at ~0.6 V/μm that is the best controlled condition we have. Furthermore, the β value has been promoted by the sweep of V_g because of the lower band energy level when V_g is applied that offer a easily tunneling environment for a number of electrons emitted from the tips of ZnO NWs. The more electrons emitted, the higher β value can achieved. While the V_g is equal to 40 V, the β value is become ~17800 which is larger than that β is ~7073 when V_g is equal to 0 V. The transconducance, g_m is also an important data to judge the ability of the gate controlled ZnO NWs field emission devices. In our study, the g_m value is about 4.0×10^{-4} S that means the better controlled V_g locates at beyond ~35V and the anode to emitter electric field is fixed on ~1.5 V/μm which can using the focusing electric field from V_g applied to converge the emission electrons approaching to the stability current density. The side gate controlled ZnO NWs field emission devices have more potential to apply in field emission display (FED) in the future.