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Nanostructured electrodes for thermionic and thermotunnel devices

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Recently, distinctive quantum features have been studied in the area of ridged quantum wells (RQWs). Periodic ridges on the surface of the quantum well layer impose additional boundary conditions on the electron wave function and reduce the quantum state density. Electrons, rejected from forbidden quantum states, have to occupy the states with higher energy. As a result, Fermi energy in RQW increases and work function (WF) decreases. We investigate low WF electrode, composed from a metal RQW layer and a base substrate. The substrate material was selected so that electrons were confined to the RQW. The WF value depends on ridge geometry and electron confinement. We calculate WF in the metal RQW films grown both on a semiconductor and metal substrates. In the case of semiconductor substrate, wide band gap materials are preferable as they allow more reduction in RQW WF. In the case of metal substrate, low Fermi energy materials are preferable. For most material pairs, the WF was reduced dramatically. Such structures, can serve as electrodes for room temperature thermionic and thermotunnel energy converters and coolers. © *2010 American Institute of Physics*. [doi:10.1063/1.3464256]

I. INTRODUCTION

Low work function (WF) electrodes[1] are essential for cold emission and room temperature operation of thermionic[2–6] and thermotunnel[7–13] energy converters and coolers. Such devices consist of plain emitter and collector electrodes, separated by the thin vacuum gap. Electrons absorb heat energy inside the emitter electrode, overcome the vacuum barrier (or tunnel through it) and release heat energy inside the collector electrode. Electrodes require materials with WF $e\times\phi=0.2-0.4$ eV (here, e is electron charge and ϕ potential). For most metals $e\times\phi>4$ eV and only some compounds show $e\times\phi=2-3$ eV. This is one order of magnitude higher than required. WF values of about 1 eV were obtained in sophisticated systems like Mo–Cs and Ag–O–Cs. However, these types of electrodes have a short lifetime even in good vacuum conditions. To overcome difficulties, quantum mechanical tunneling was utilized. Tunneling through vacuum nanogap allows sufficiently large currents from the electrodes, having relatively high $e\times\phi$ values. It was found that image force reduces potential barrier and increases tunneling current, giving a cooling power of 100 W/cm^2 for $e\times\phi\approx 1$ eV (Ref. 7) in mixed thermotunnel and thermionic regime. Electrons were filtered by collector coating, to increase the cooling coefficient[8] and conformal electrode growth technology was developed.[9] However, vacuum nanogap device appears extremely difficult to fabricate[9–11] as it requires an electrode spacing of 5–10 nm. If an $e\times\phi<1$ eV electrode could be obtained, poor thermionic regime can be realized at increased electrode spacing. Fabrication of wide vacuum gap, using conformal electrode technology, is much more straightforward. Low WF energy converters are essential for heat to electricity direct conversion in the temperature range 400–1000 K in which waste heat is available from the combustion sources. Low WF coolers are essential for integrated circuit cooling and other applications where low weight and ecological purity are major requirements.

Here, we offer to reduce $e\times\phi$ using surface nanostructuring. The electrode is coated by the metal ridged quantum well (RQW) layer. Its operation is based on the effect of quantum state depression. Periodic ridges, fabricated on the layer surface, impose additional boundary conditions on the electron wave function. Supplementary boundary conditions forbid some quantum states for free electron and the quantum state density in the energy $\rho(E)$ reduces. According to Pauli's exclusion principle, electrons rejected from the forbidden quantum states have to occupy the states with higher E. As result the Fermi energy E_F increases and $e\times\phi$ decreases.[14]

The quantum state density in the RQW (Fig. 1) reduces G times

$$\rho(E)=\rho_0(E)/G, \tag{1}$$

where $\rho_0(E)$ is the density of states in a conventional quantum well layer of thickness L ($a=0$) and G is the geometry factor introduced in Ref. 16. For the case $a\ll L,w$ and within the range $5<G<10$, the following approximate expression (obtained in Ref. 15) can be used

$$G\approx L/a, \tag{2}$$

where a is the ridge height and L is the RQW layer thickness (Fig. 1). Density of forbidden quantum states is

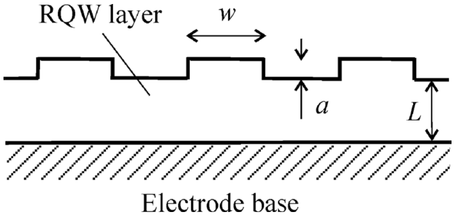

FIG. 1. Cross section of electrode coated by RQW.

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